Our Restless Planet

Understanding Earthquakes and Land Surface Processes from Space

Andrea Donnellan

June 19, 2004

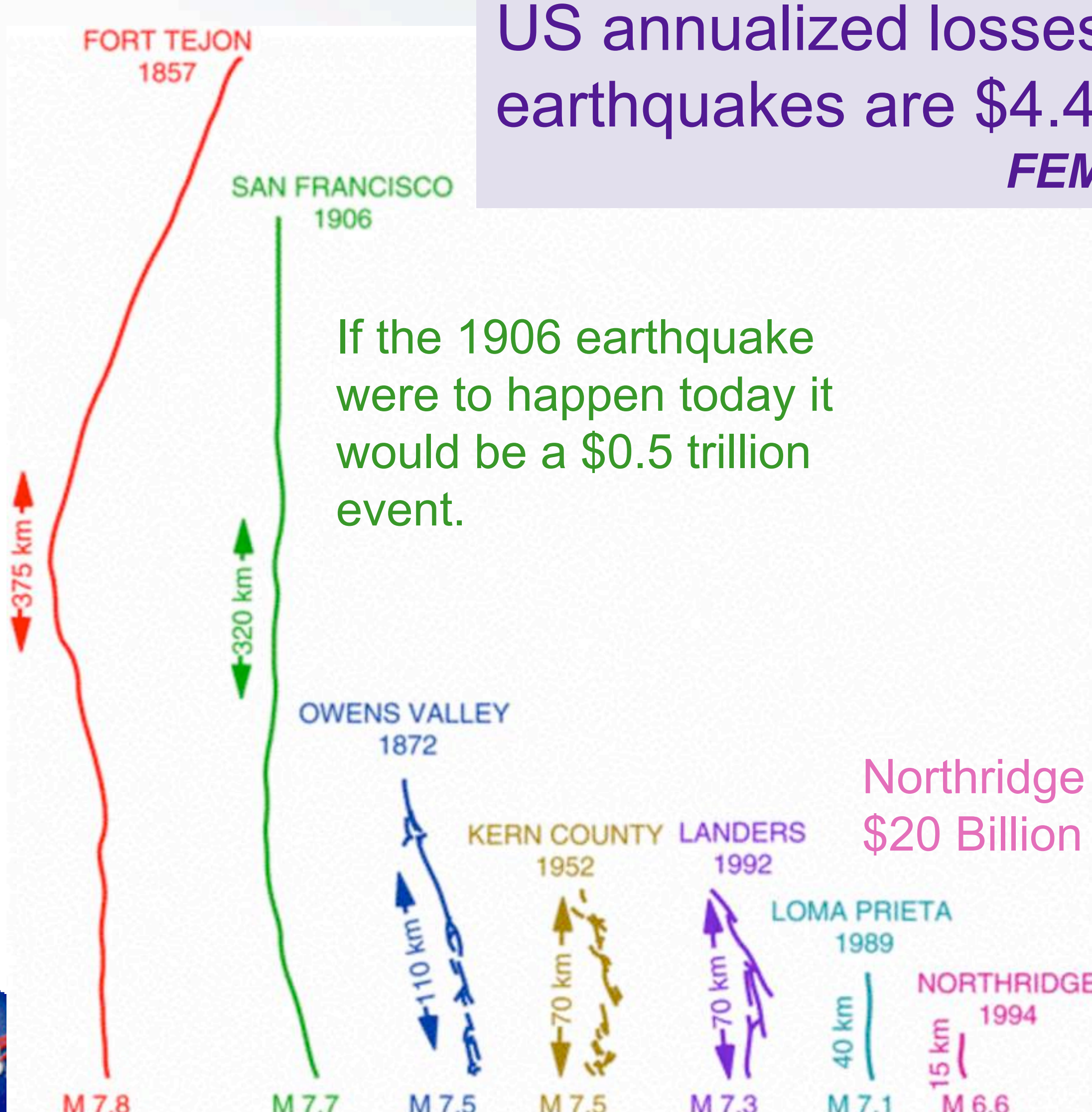
Caltech Alumni College

Jet Propulsion Laboratory
California Institute of Technology

Earthquake Damage Depends on Location and Size

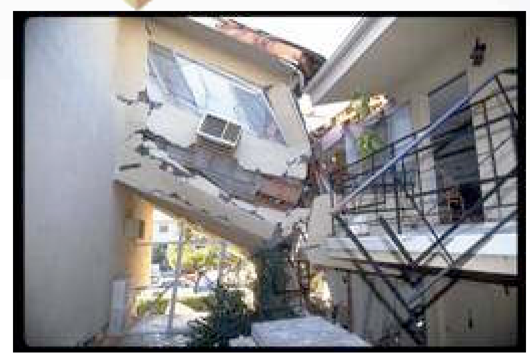
US annualized losses from earthquakes are $4.4B/yr.

FEMA 2000



If the 1906 earthquake were to happen today it would be a $0.5 trillion event.

Northridge was a $20 Billion event



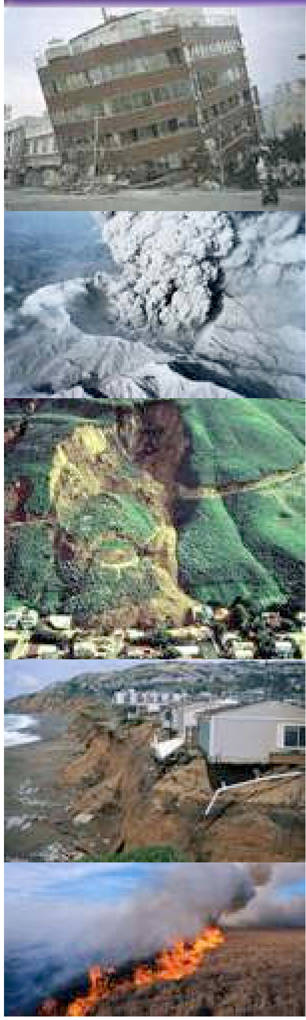
Jet Propulsion Laboratory
California Institute of Technology

NASA's Solid Earth Science Working Group

- Group was formed in Summer of 2000
- Published *Living on a Restless Planet* in November 2002
- 25 year vision and strategy for solid Earth science within NASA

Jet Propulsion Laboratory
California Institute of Technology

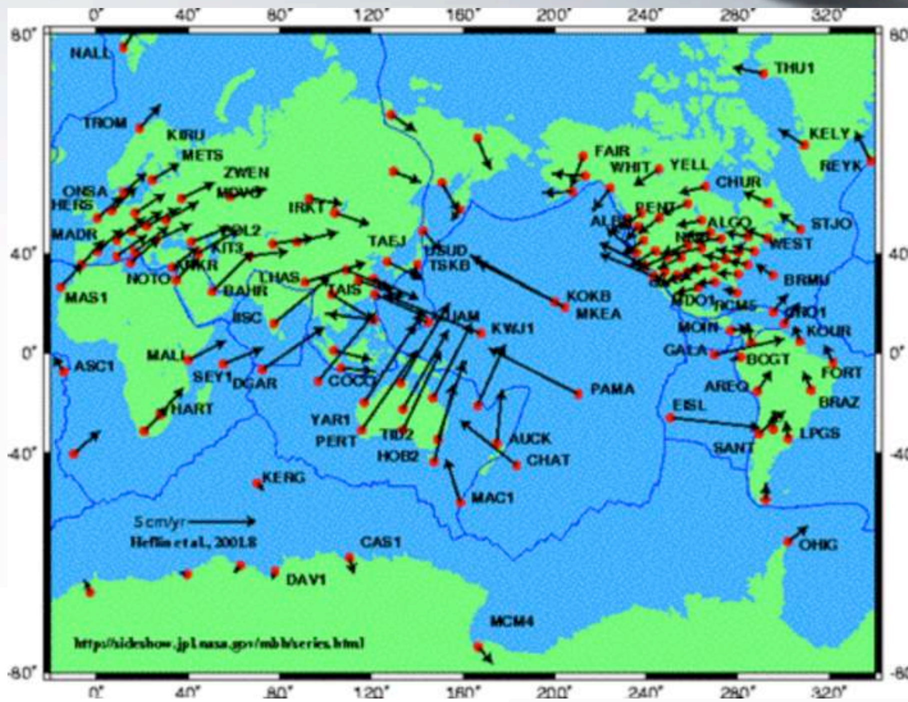
Fragile Foundations



- The solid Earth is a dynamic component of the Earth system.
  - Natural hazards such as earthquakes, volcanoes, landslides, floods, sea level rise, and wildland fires are major societal threats.
- Characterizing and understanding the underlying forces is required to move toward predictive capabilities.
- These capabilities will lead to a deeper scientific understanding of our planet and an improved assessment and mitigation of natural hazards.

Jet Propulsion Laboratory
California Institute of Technology

Global Perspectives



- Key interactions show the interconnected nature of the Earth system.
- Solid Earth science requires global observations and a diverse program.
- Space-based observations provide a unique capability for global sampling and studying episodic events.
- NASA leadership will open new scientific opportunities.

Jet Propulsion Laboratory
California Institute of Technology

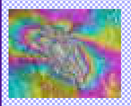
NASA Earth Science Enterprise Goal and Leading Solid Earth Science Questions

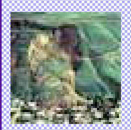
Observe, understand, and model the Earth system to learn how it is changing and understand the consequences for life on Earth.

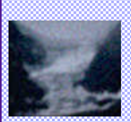
What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes?

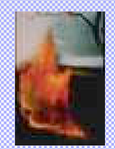
How is the Earth's surface being transformed and how can such information be used to predict future changes?

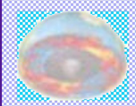
Scientific Challenges Identified by SESWG

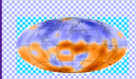
1.  What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?

2.  How do tectonics and climate interact to shape the Earth's surface and create natural hazards?

3.  What are the interactions among ice masses, oceans, and the solid Earth and their implications for sea level change?

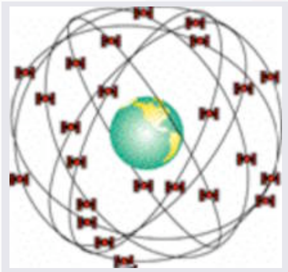
4.  How do magmatic systems evolve and under what conditions do volcanoes erupt?

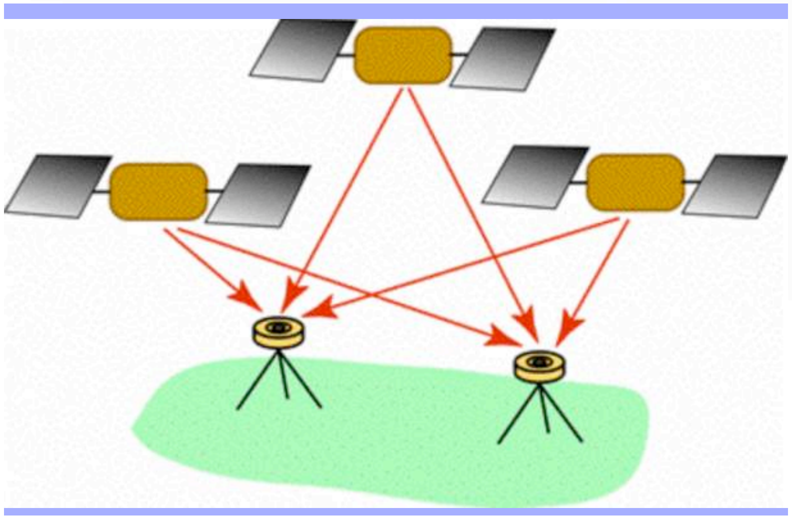
5.  What are the dynamics of the mantle and crust and how does the Earth's surface respond?

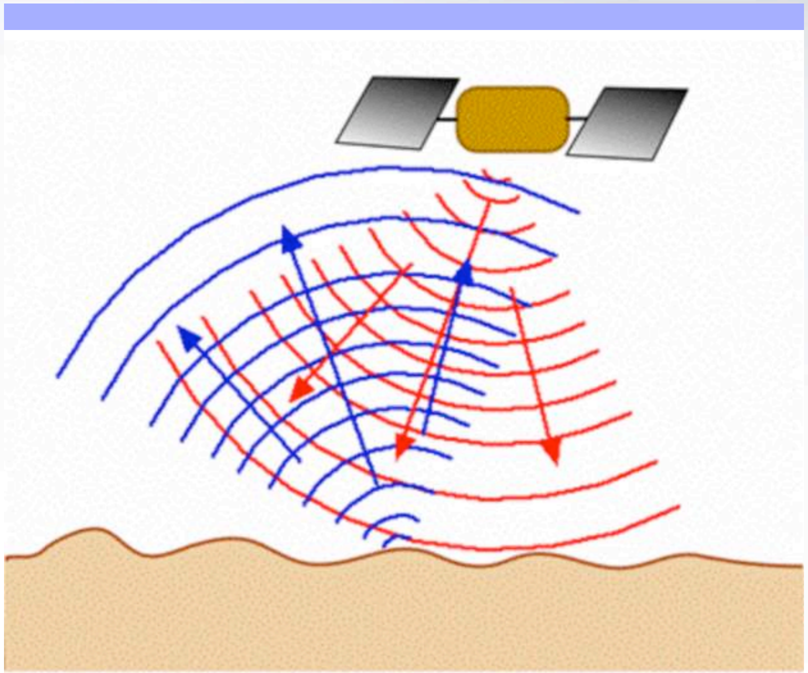
6.  What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?

Jet Propulsion Laboratory
California Institute of Technology

GPS and InSAR







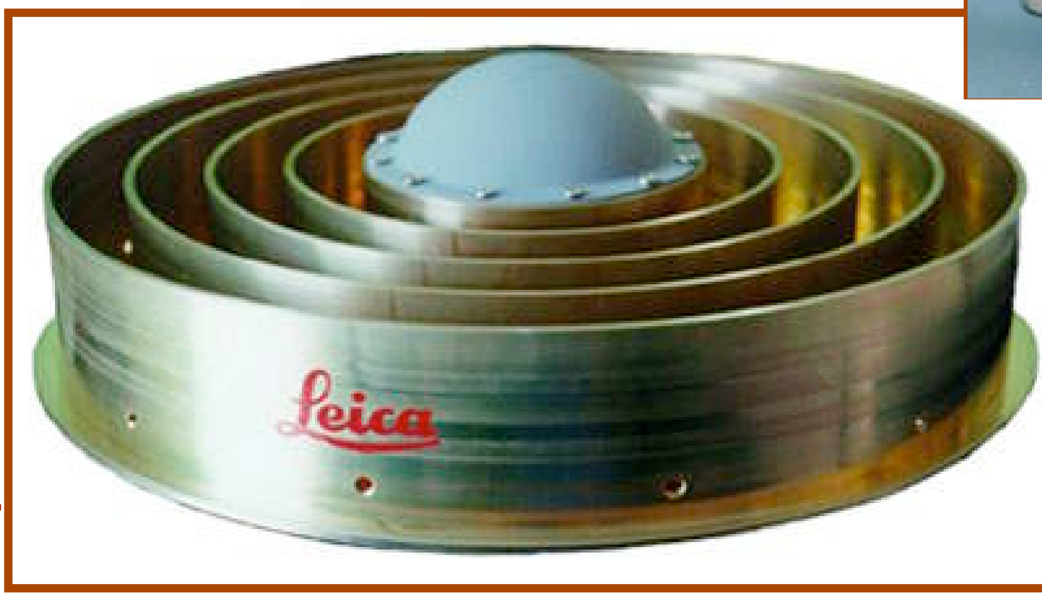
GPS Constellation and Network

Synthetic Aperture Radar

Jet Propulsion Laboratory
California Institute of Technology

Handheld Versus Precise GPS Equipment

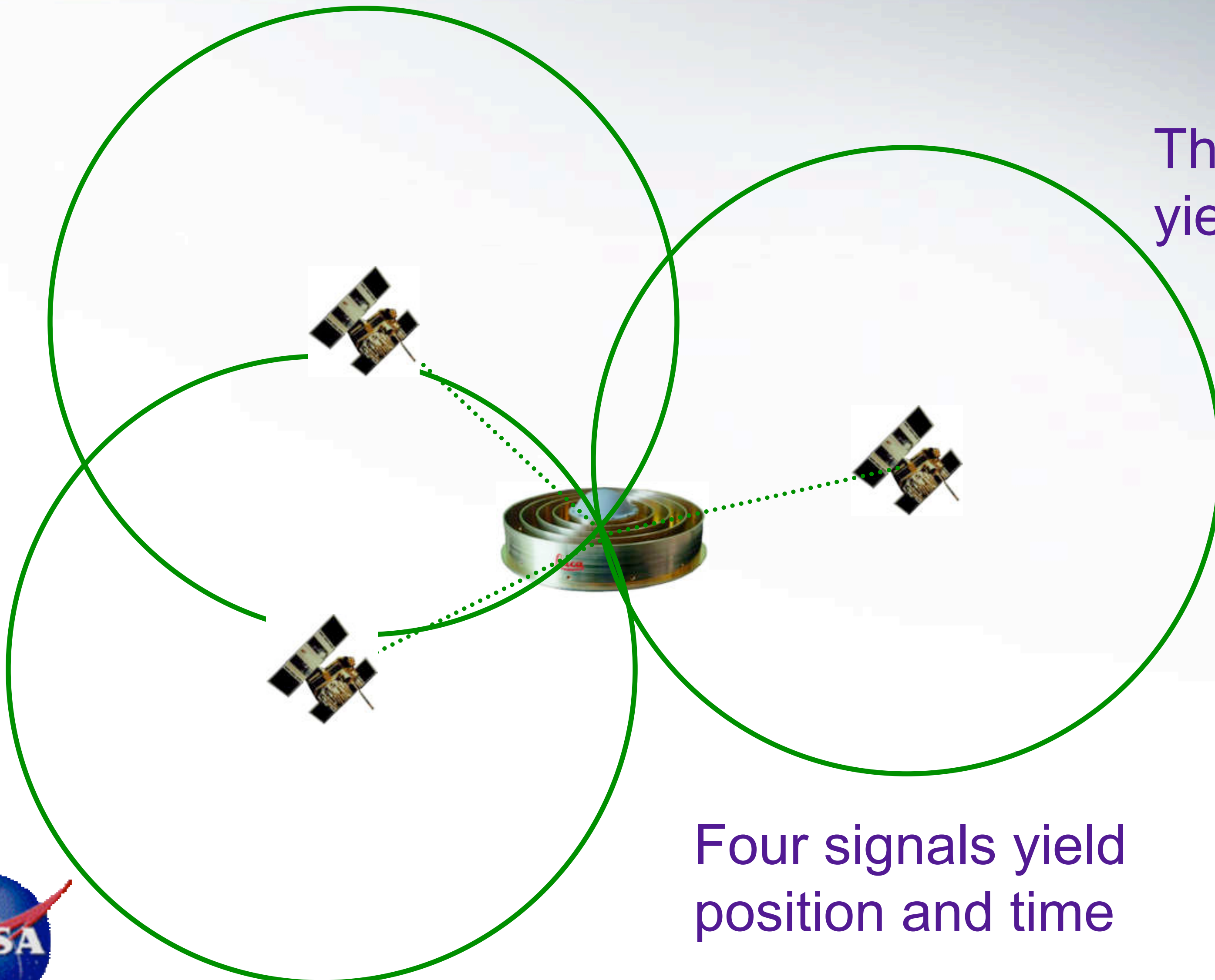
Han



Precision
GPS Antenna

Jet Propulsion Laboratory
California Institute of Technology

Point Positioning

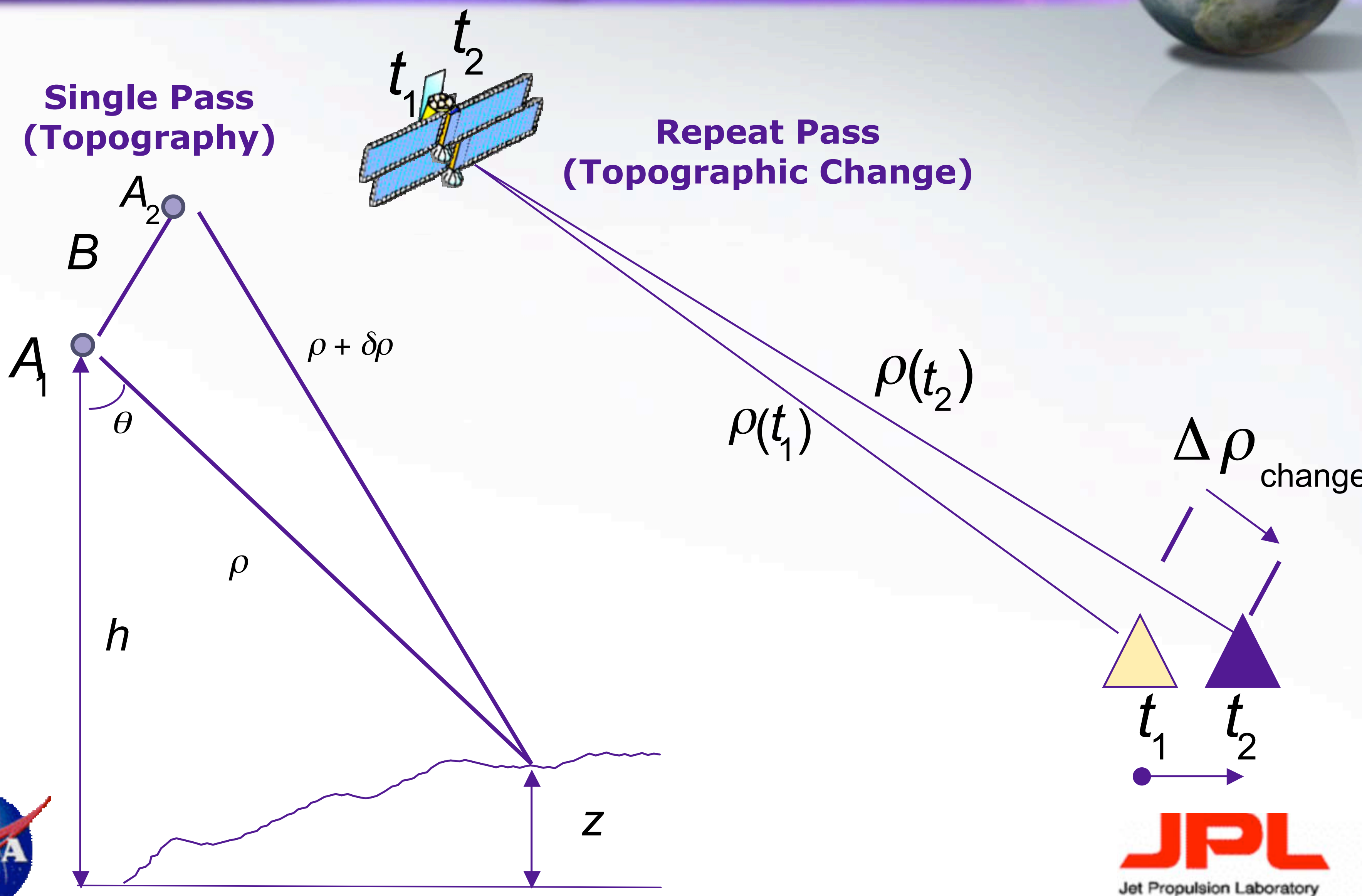


Three signals yield position

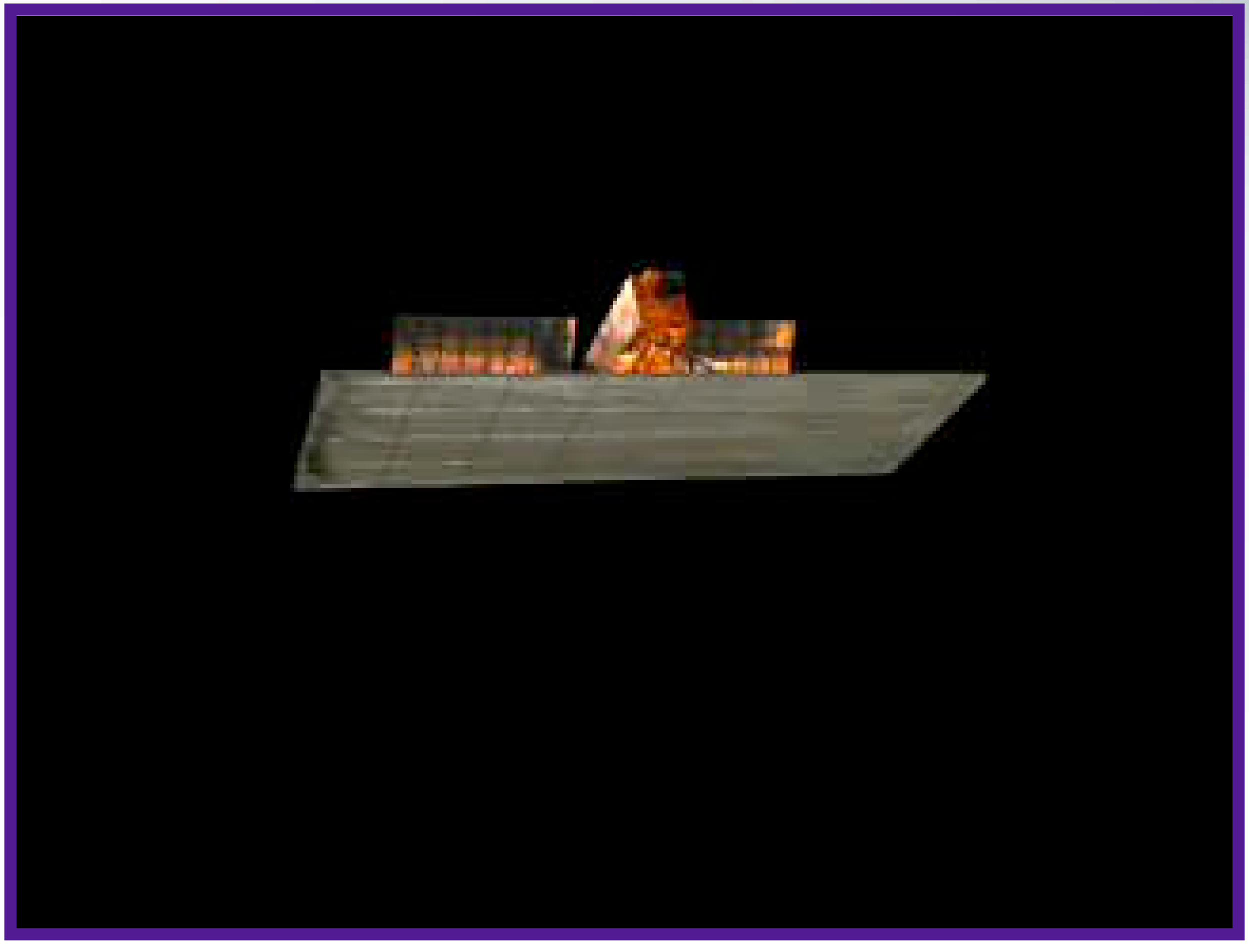
Four signals yield position and time

Jet Propulsion Laboratory
California Institute of Technology

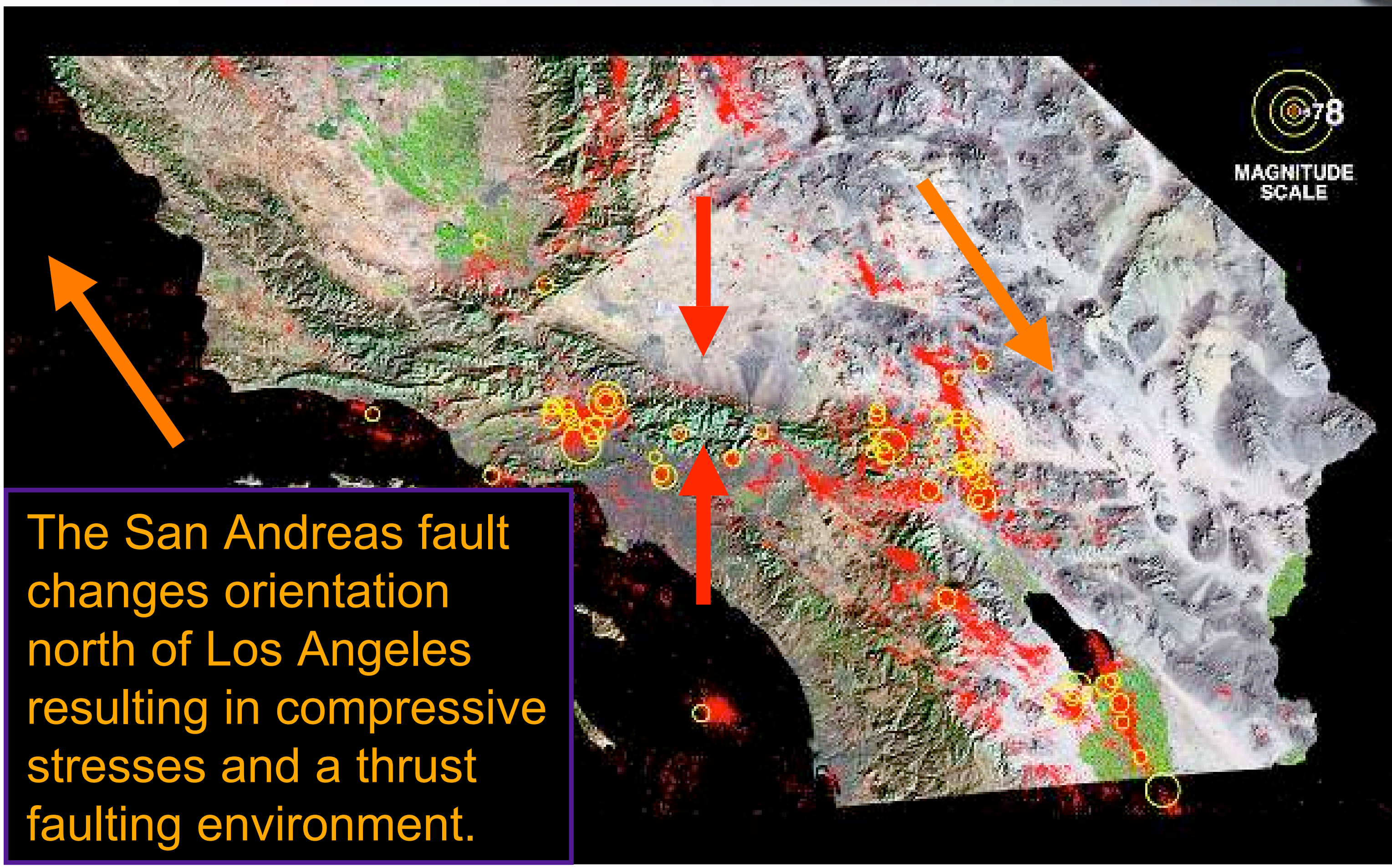
Interferometry Basics



InSAR Concept



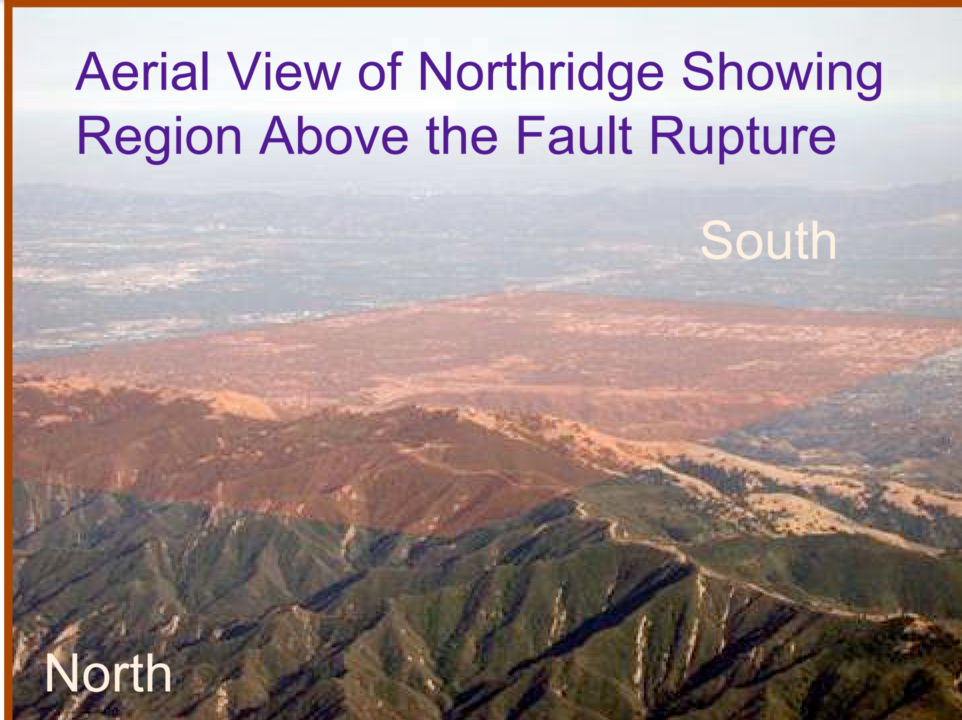
Southern California is Actively Deforming



The San Andreas fault changes orientation north of Los Angeles resulting in compressive stresses and a thrust faulting environment.

JPL
Jet Propulsion Laboratory
California Institute of Technology

GPS Results Indicated Active Faults Near Northridge

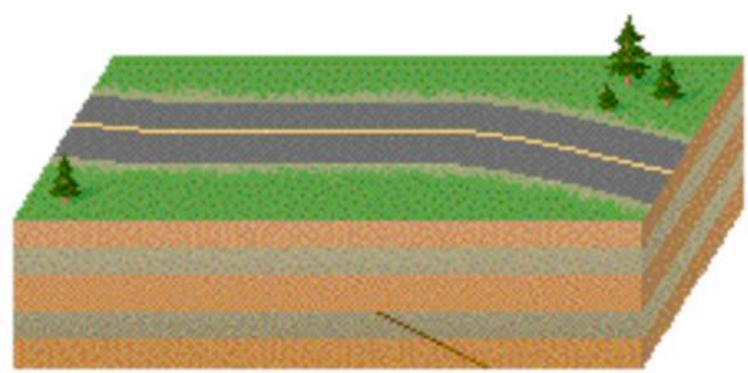


Aerial View of Northridge Showing Region Above the Fault Rupture

"…would yield an earthquake of moment magnitude $M_w \approx 6.4$… and a $M_w \approx 6$ earthquake is still large and potentially damaging."

Donnellan et al., Nature, November 25, 1993.

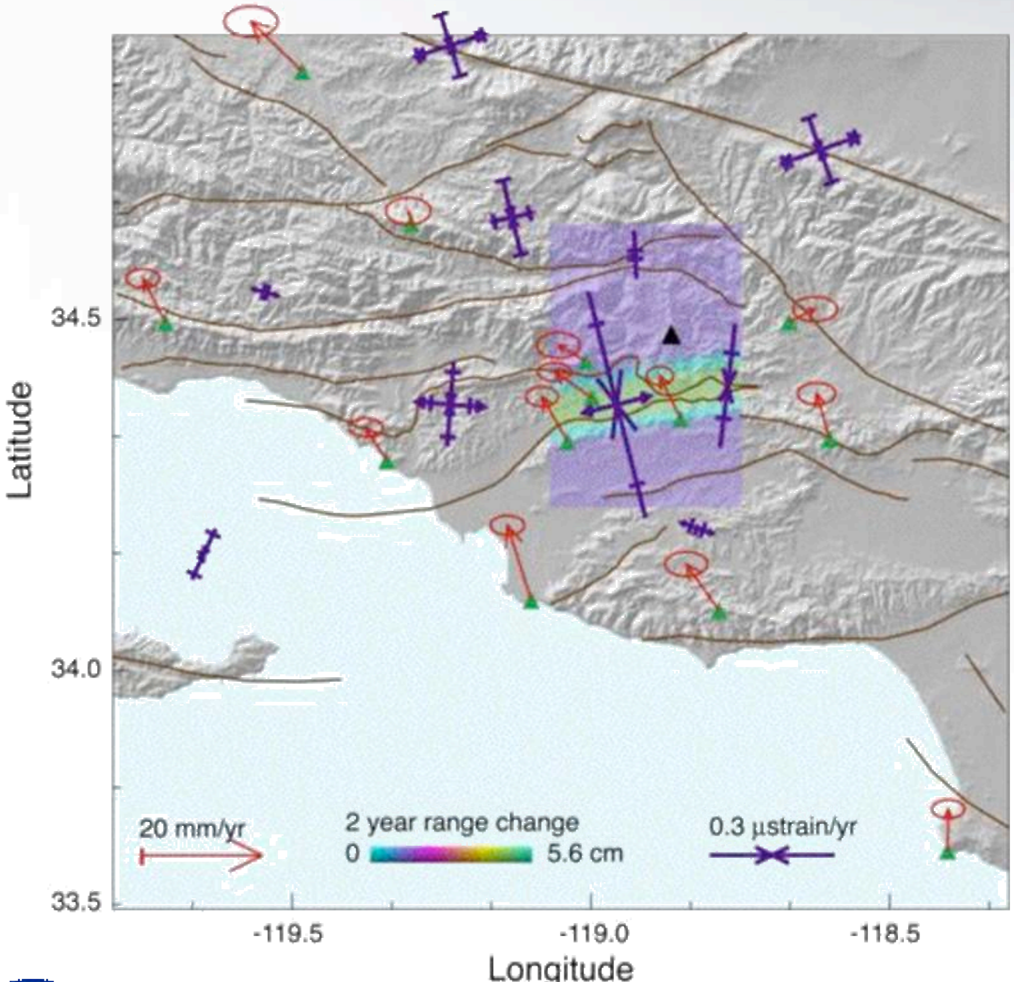
The mountains grew 40 cm during the M 6.7 Northridge earthquake



Northridge occurred on a blind thrust fault

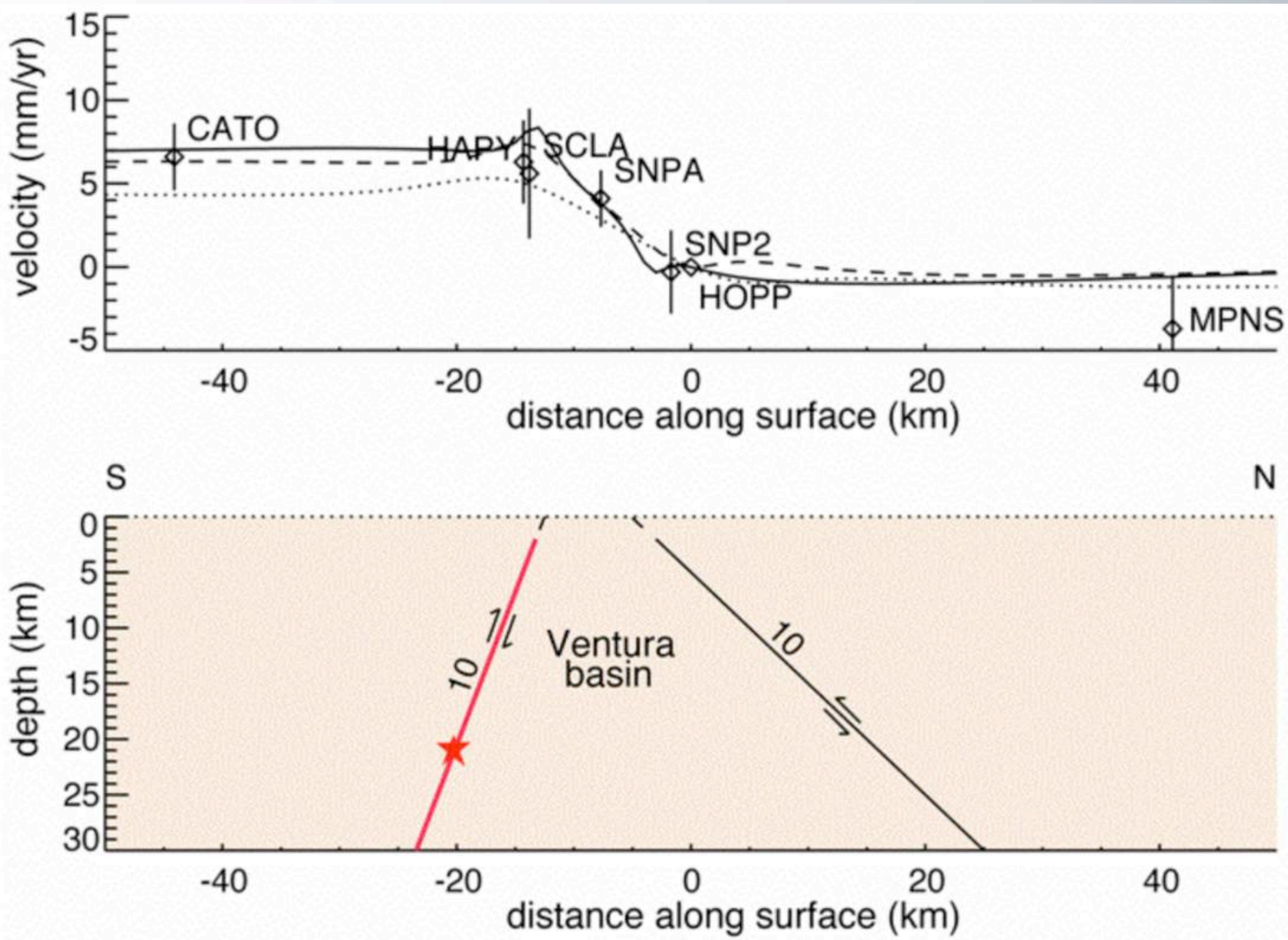

GPS 0113

Pre-Northridge GPS Results



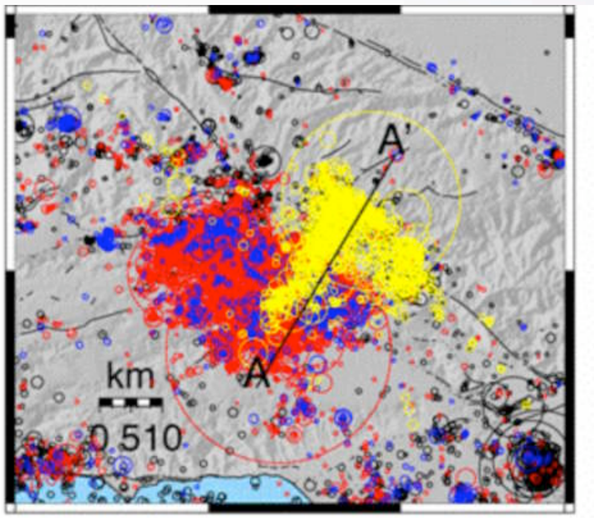
- Block like motion north and south of the basin
- High observed strain rates.
- Thrust faulting environment within the basin
- Strike-slip environment along the San Andreas

GPS Velocity Profile and Cross Section

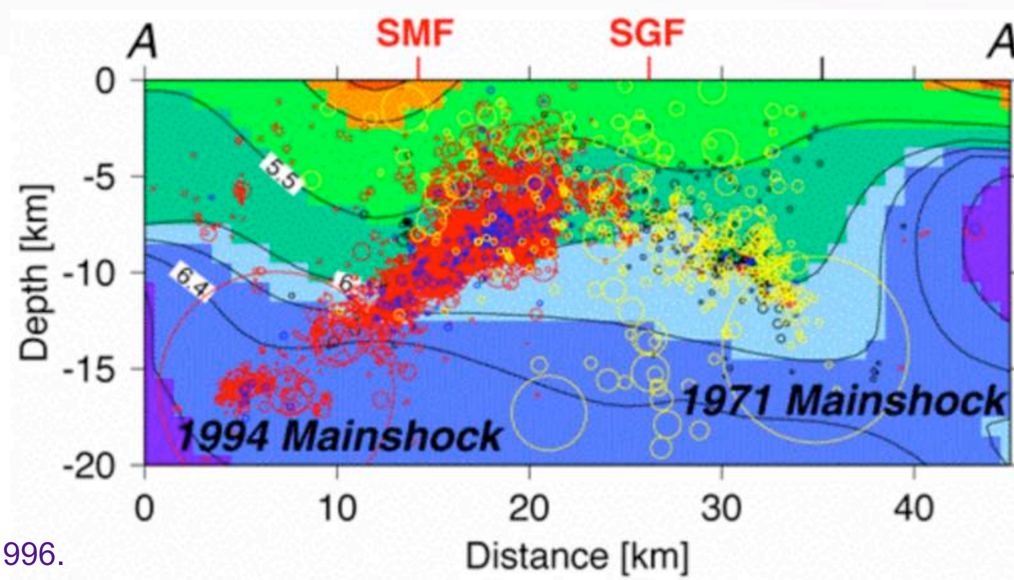


Northridge Seismicity

Map View



- The earthquake occurred on a conjugate plane of the 1971 San Fernando Earthquake.
- Yellow dots show San Fernando aftershocks.
- Red dots show Northridge aftershocks
- Blue dots are other events.

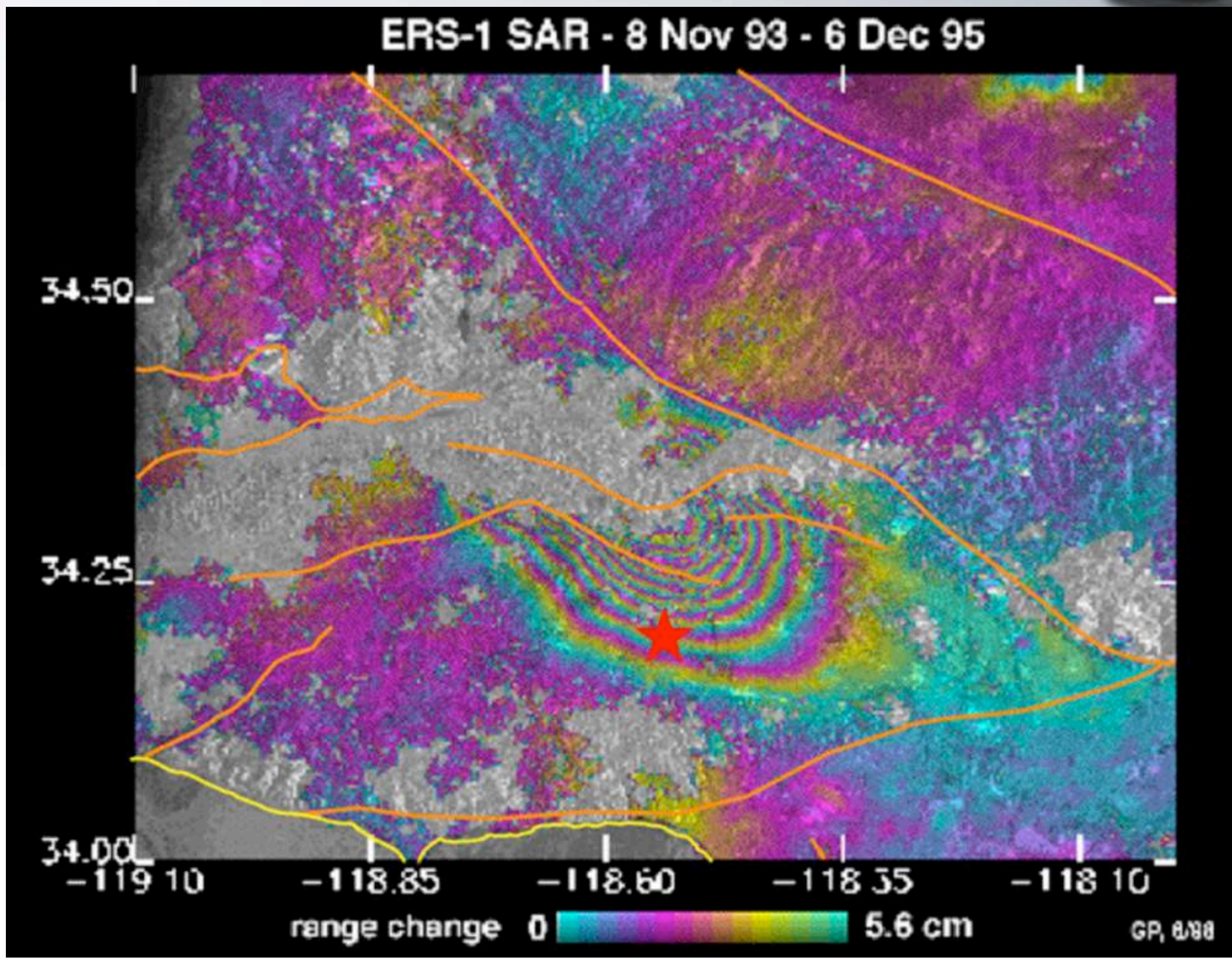


Most of the aftershocks lie on the mainshock rupture planes.

Hauksson,Geophys. Res. Lett., 1996.

The Northridge Earthquake was Observed with InSAR

The Mountains grew 40 cm as a result of the Northridge earthquake.

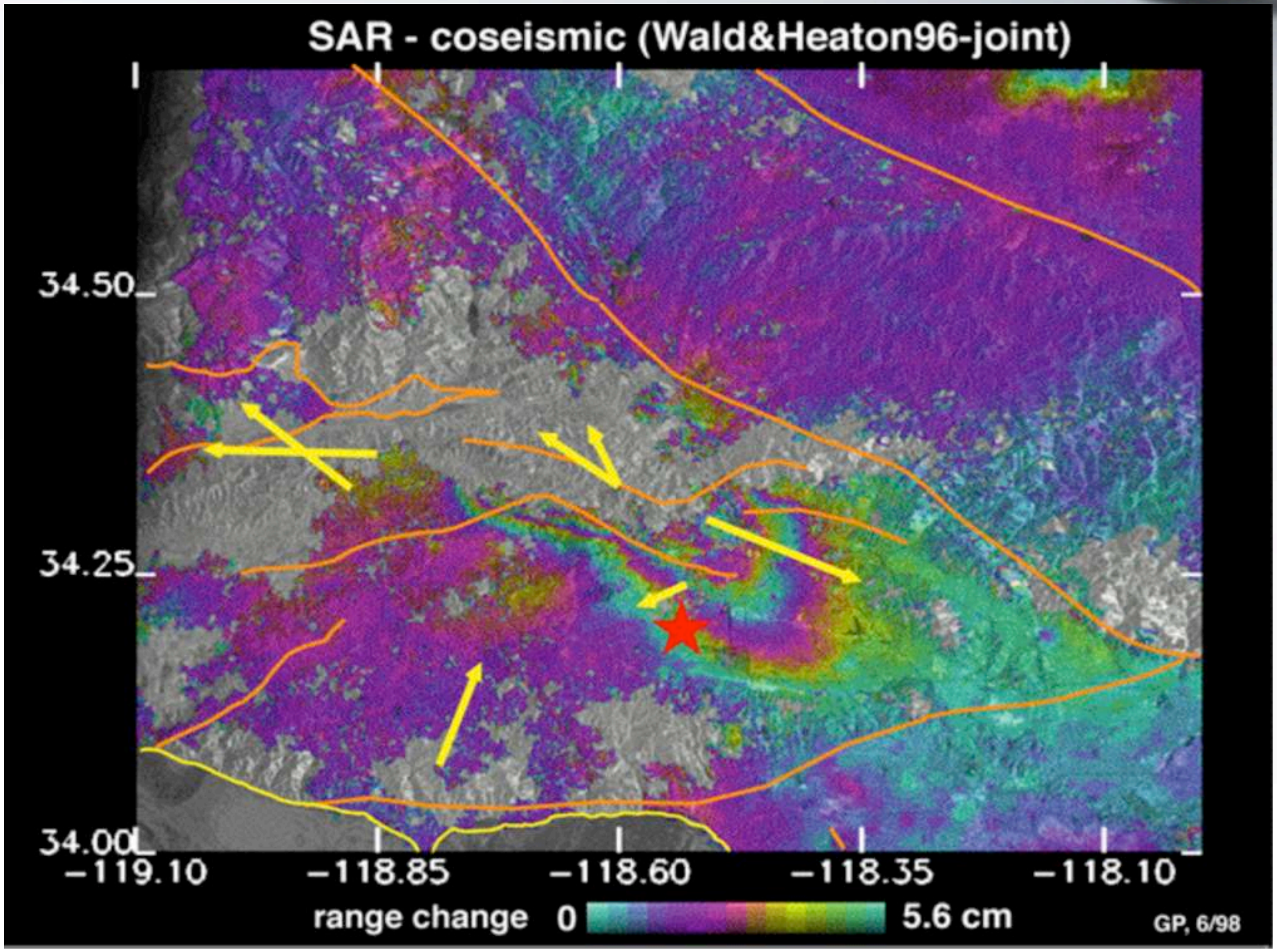


1993–1995 Interferogram

Jet Propulsion Laboratory
California Institute of Technology

Postseismic Motion was Observed with InSAR and GPS

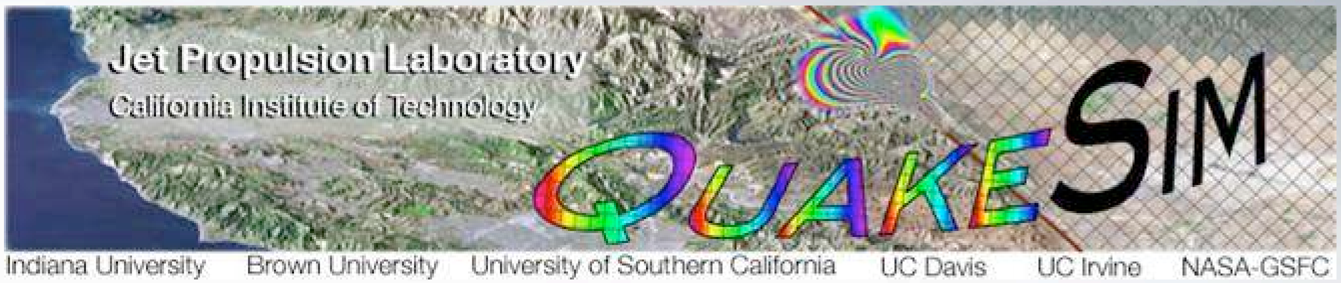
The Mountains continued to grow 12 cm for two years following the earthquake



90% of the motion was quiet and not observable with seismometers

Jet Propulsion Laboratory
California Institute of Technology

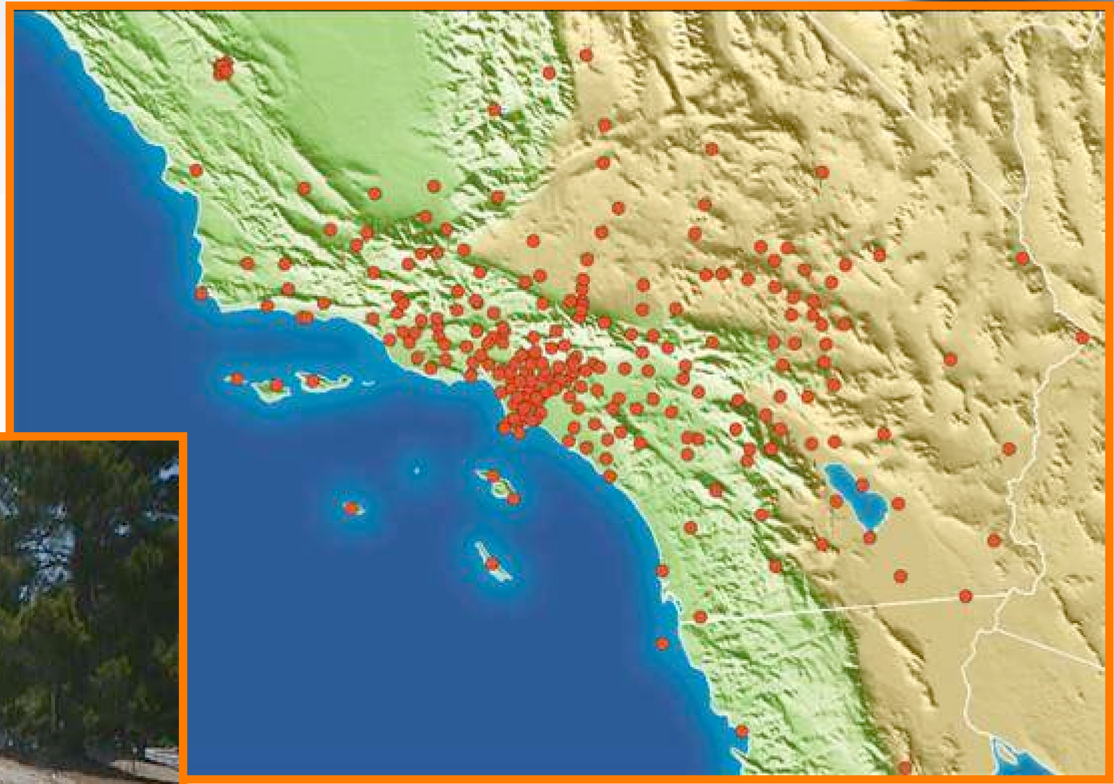
Northridge Earthquake Deformation



Jet Propulsion Laboratory
California Institute of Technology

Southern California Integrated GPS Network

250 Station Continuously Operating GPS Network



Jet Propulsion Laboratory
California Institute of Technology

Deformation Continues in the Los Angeles Area

Recent GPS Results Show Concentrated Deformation Near Downtown Los Angeles

MSNBC TV News

NBC NIGHTLY NEWS WITH TOM BROKAW

Los Angeles is moving, literally

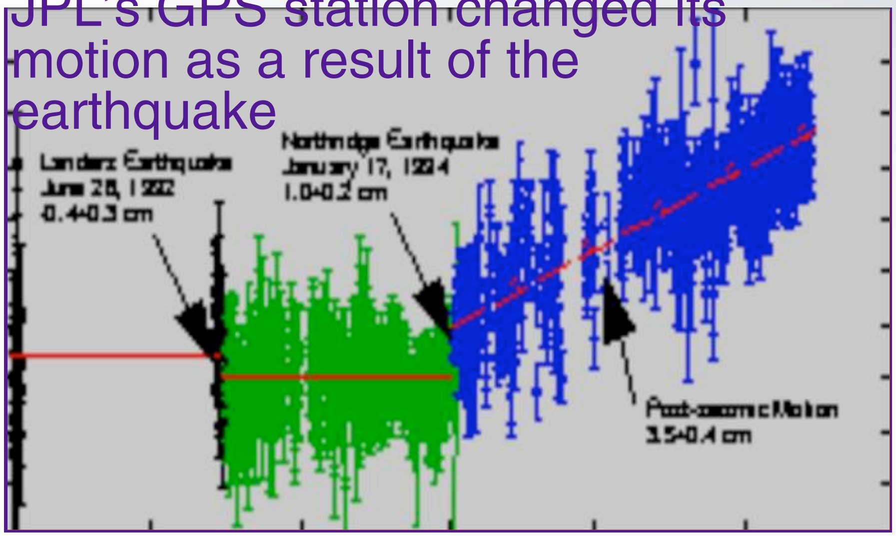
Nick Ut / AP file

LOS ANGELES, August 4 — Scientists at the Jet Propulsion Lab in Pasadena, Calif., have made measurements that suggest that downtown Los Angeles is moving toward the San Gabriel Mountains, and that a new mountain range is being formed beneath Hollywood.

Jet Propulsion Laboratory
California Institute of Technology

The Northridge Earthquake Affected the Sierra Madre Fault 30 Km Away

JPL's GPS station changed its motion as a result of the earthquake

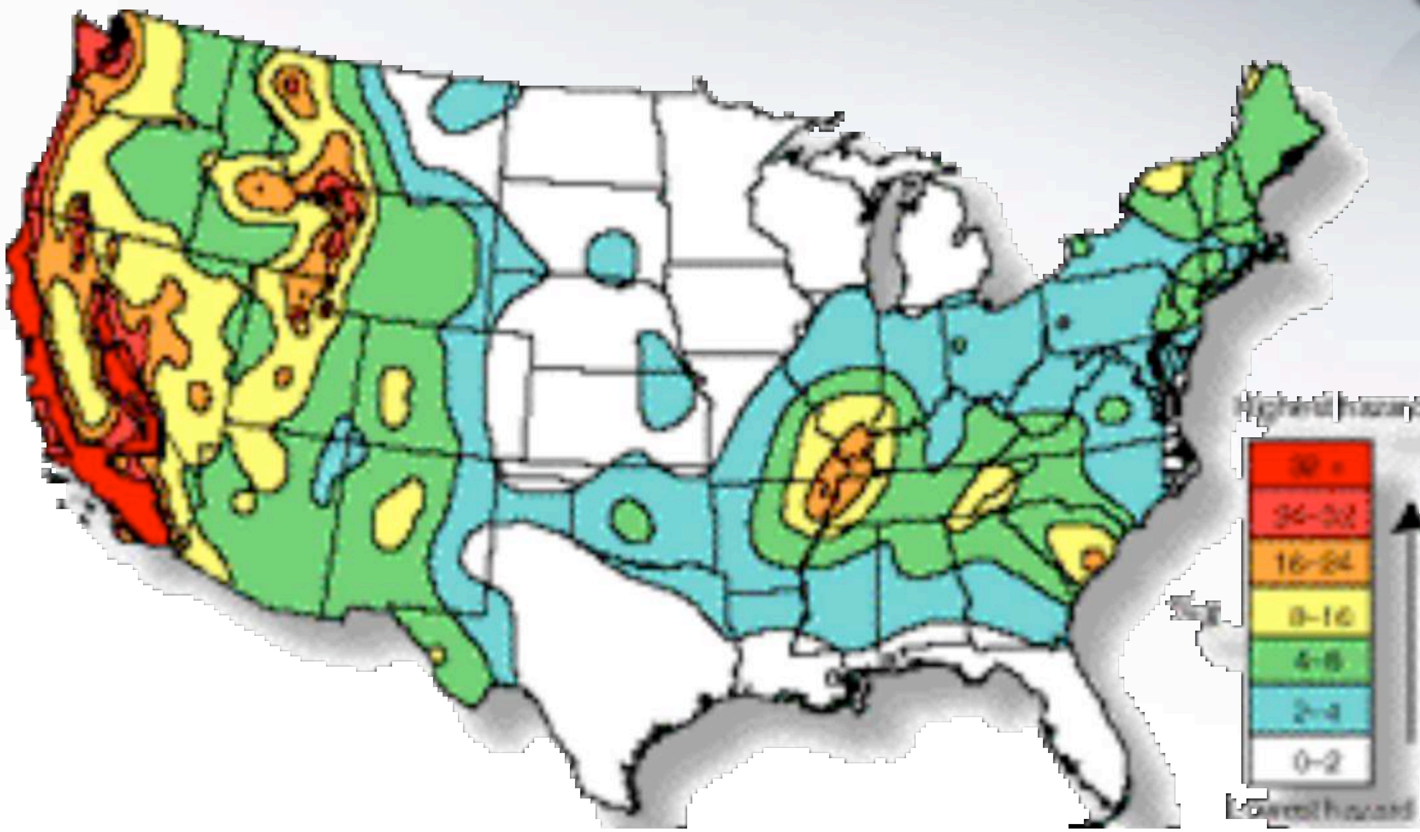


Sierra Madre Fault

The earthquake probably triggered shallow slip on the Sierra Madre Fault.

This was one example where long range fault interactions were observed.

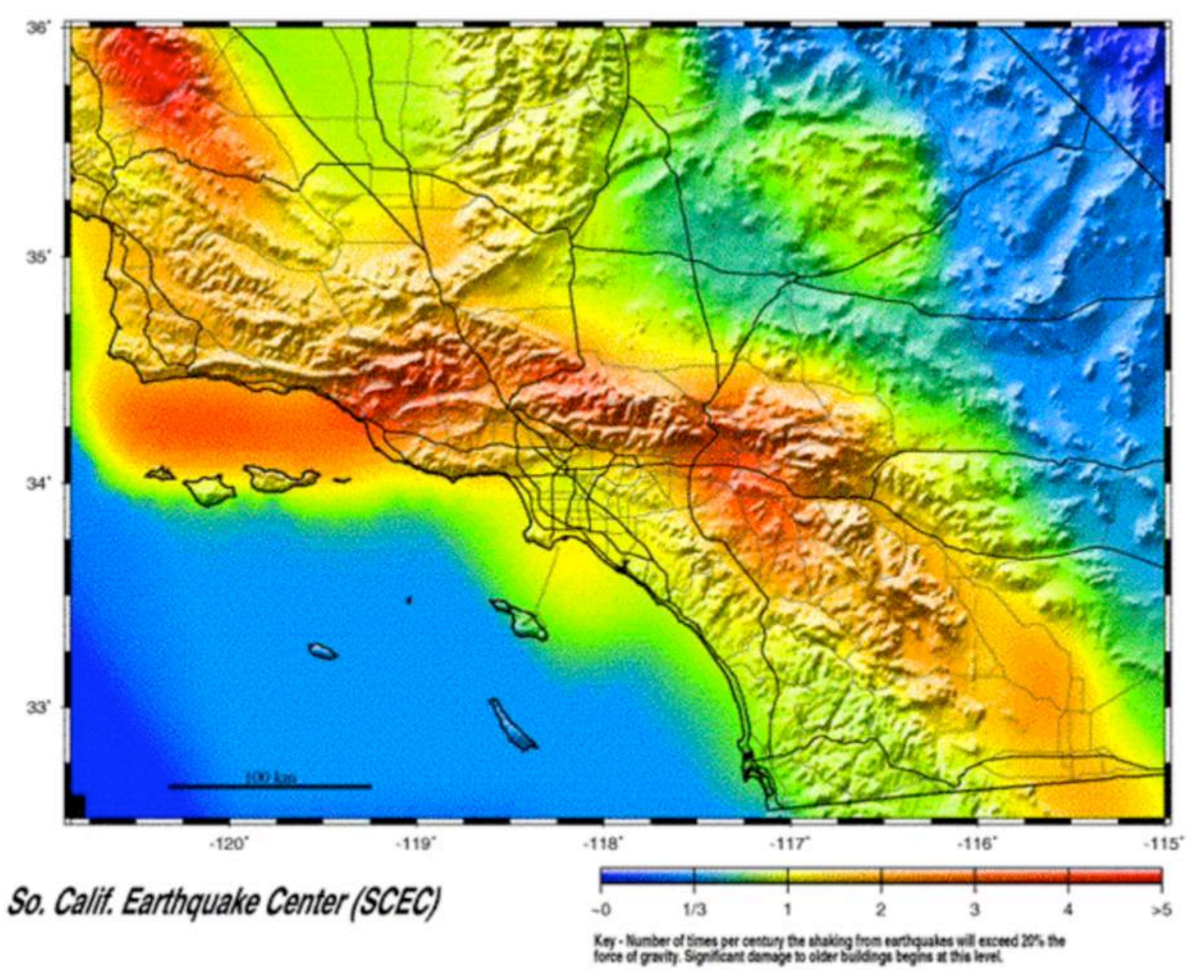
US Earthquake Hazard Map



US Annualized losses from earthquakes are $4.4 B/yr

Jet Propulsion Laboratory
California Institute of Technology

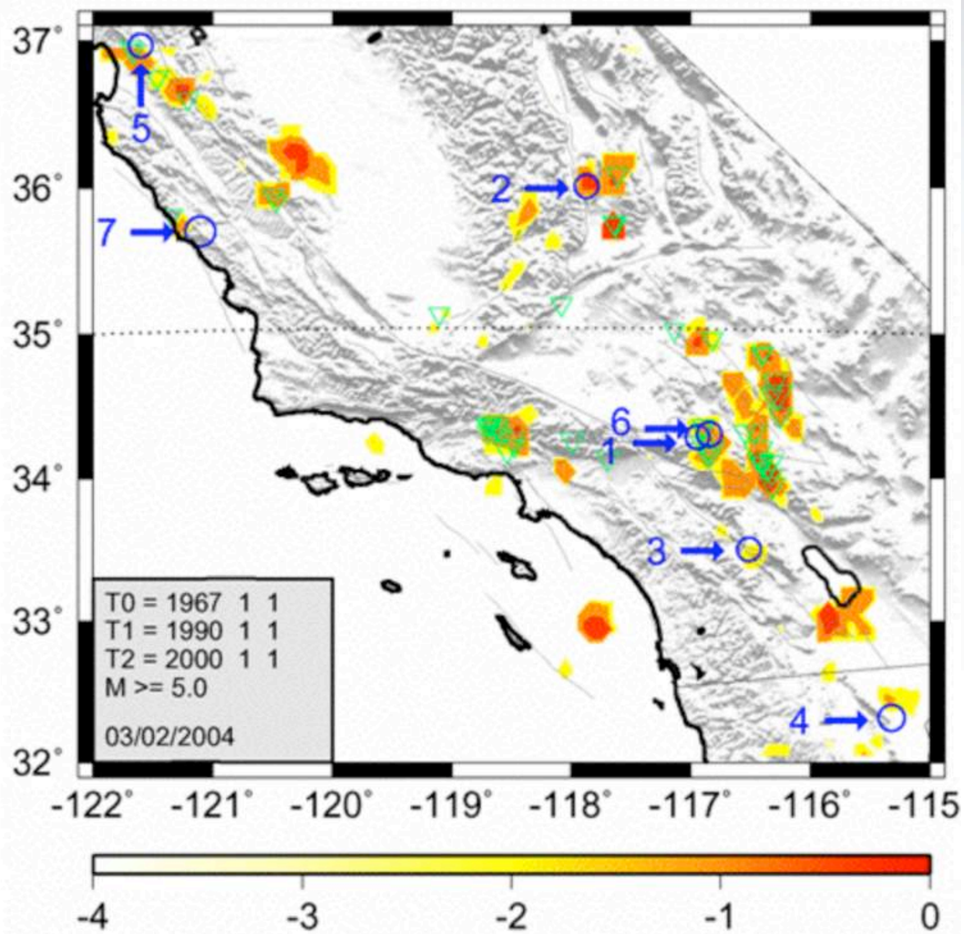
Southern California Earthquake Hazard Map



Half of the US earthquake risk lies in California.
25% of the risk is in southern California.

Jet Propulsion Laboratory
California Institute of Technology

Real-time Earthquake Forecast



Plot of Log_{10} $\Delta P(x)$

Potential for large earthquakes, M ≥ 5, ~ 2000 to 2010

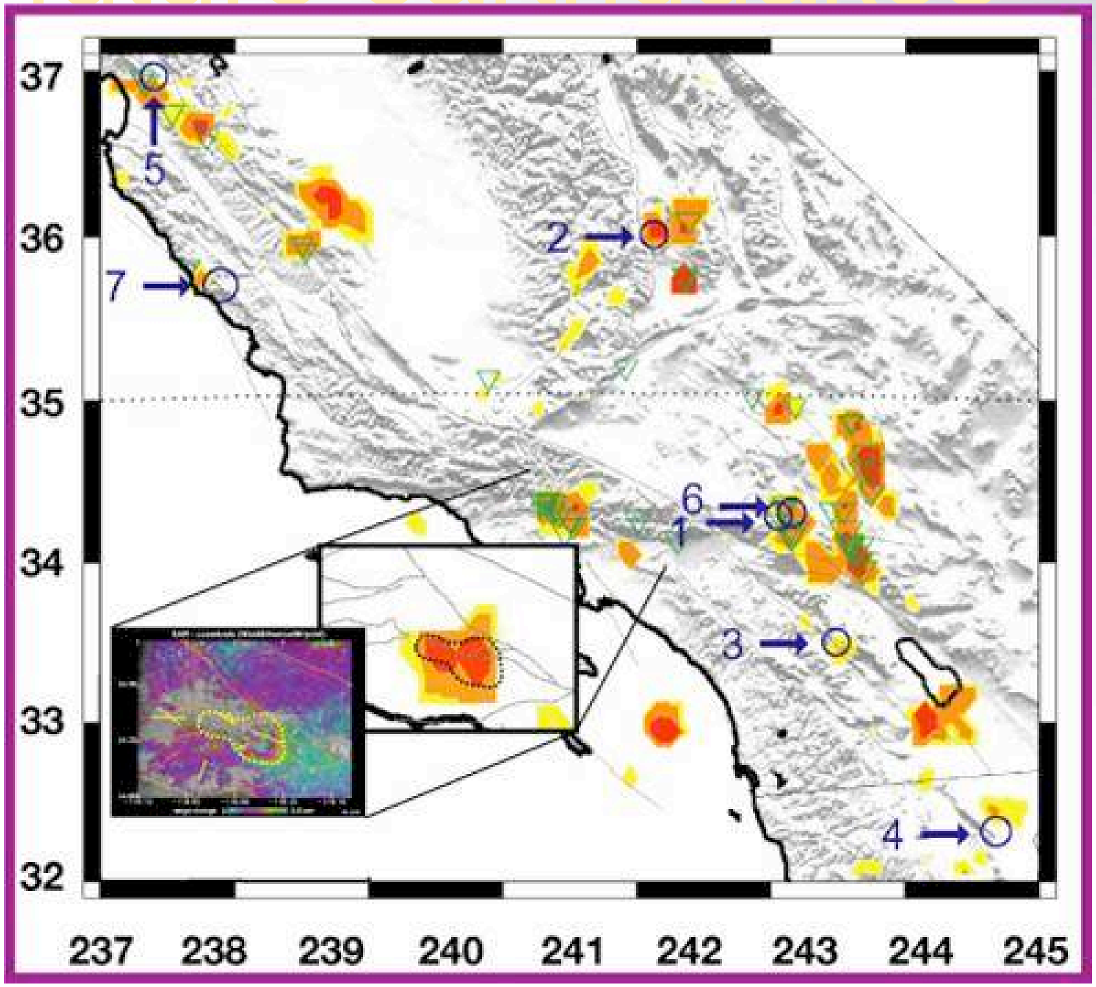
Seven large events with M ≥ 5 have occurred on anomalies, or within the margin of error:

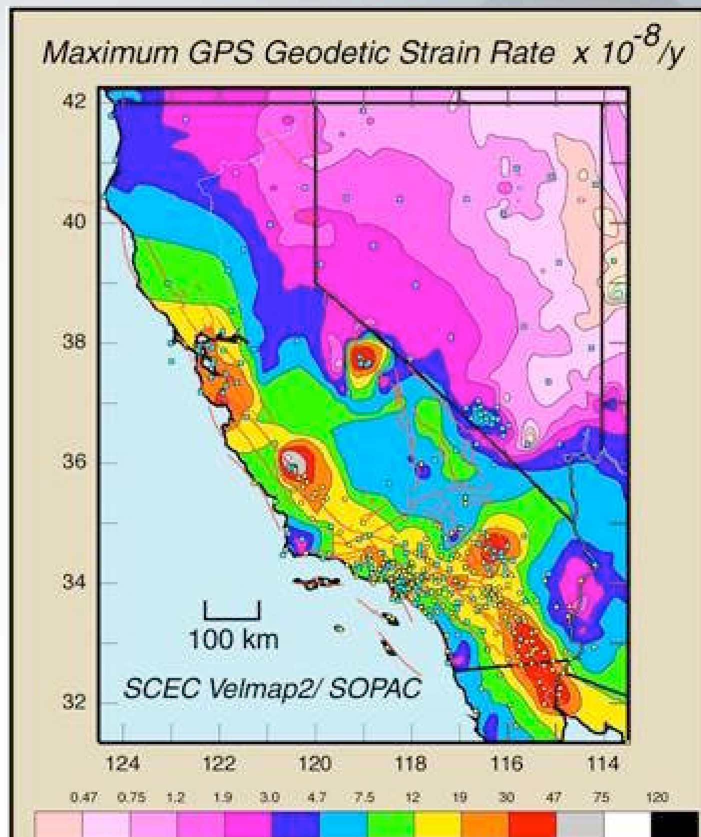
1. Big Bear I, M = 5.1, Feb 10, 2001
2. Coso, M = 5.1, July 17, 2001
3. Anza, M = 5.1, Oct 31, 2001
4. Baja, M = 5.7, Feb 22, 2002
5. Gilroy, M=4.9 - 5.1, May 13, 2002
6. Big Bear II, M=5.4, Feb 22, 2003
7. San Simeon, M = 6.5, Dec 22, 2003

JB Rundle, KF Tiampo, W. Klein, JSS Martins, PNAS, v99, Supl 1, 2514-2521, Feb 19, 2002;
KF Tiampo, KF Tiampo, JB Rundle, S. McGinnis, S. Gross and W. Klein, Europhys. Lett., 60, 481-487, 2002

Jet Propulsion Laboratory
California Institute of Technology

GPS and InSAR anomalies may show the locations of future earthquakes



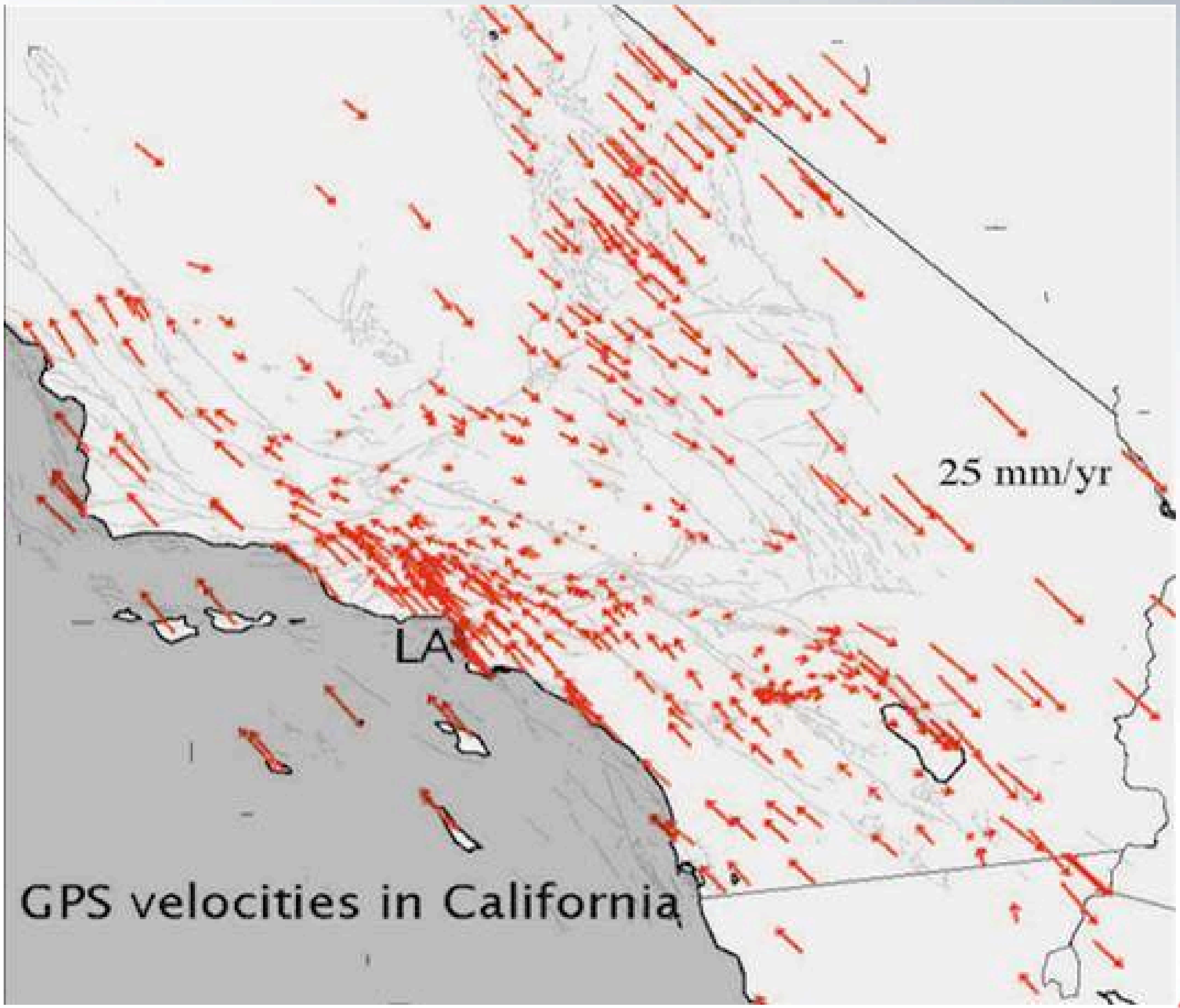


Courtesy of Steve Ward

New data and models should substantially refine hazard maps, allowing for improved prioritization of retrofitting and risk mitigation.

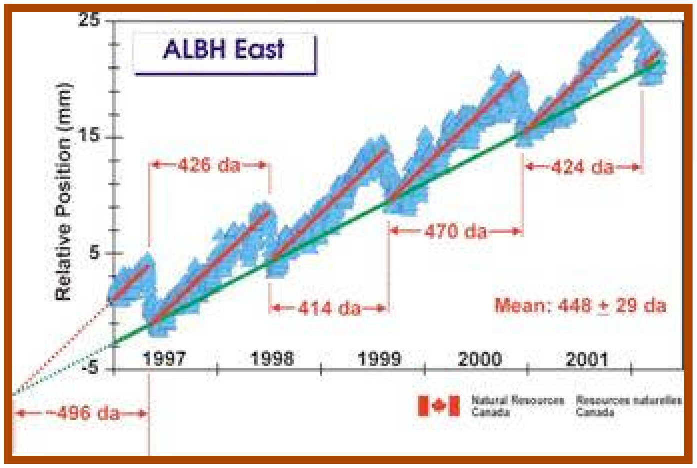
JPL
Jet Propulsion Laboratory
California Institute of Technology

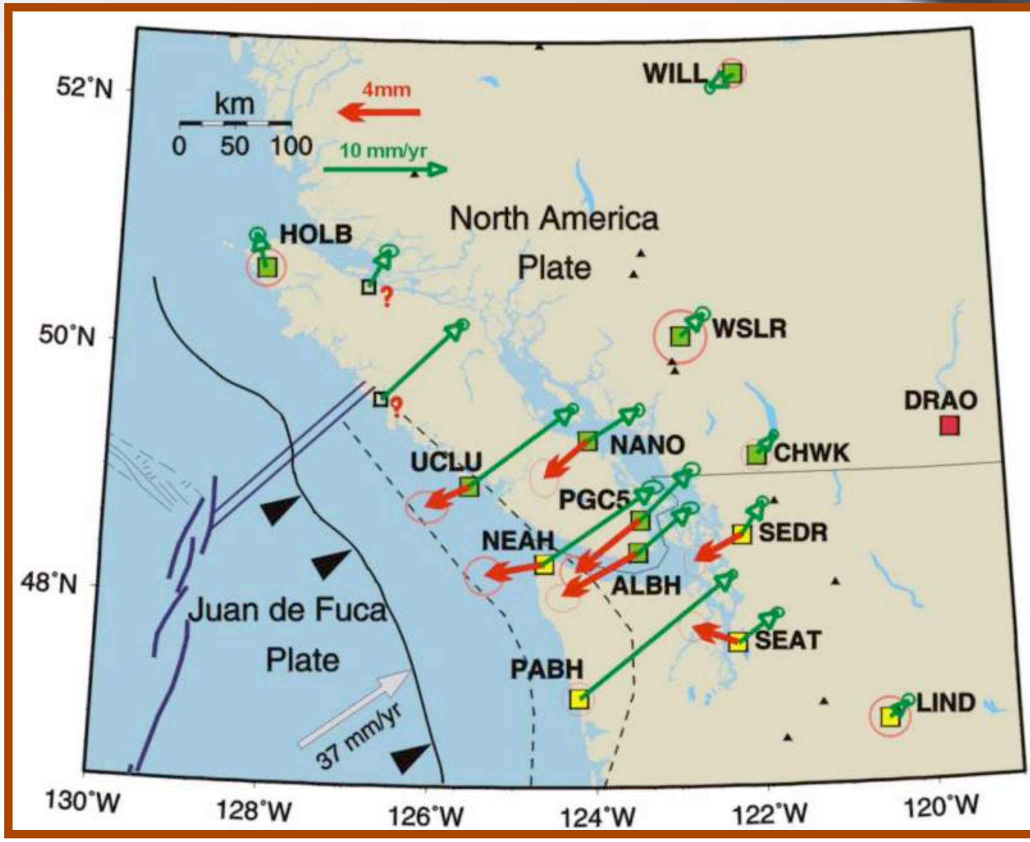
Density of Ground Stations is Increasing



Space-Based Methods are Showing an Increasing Number of Slow Events

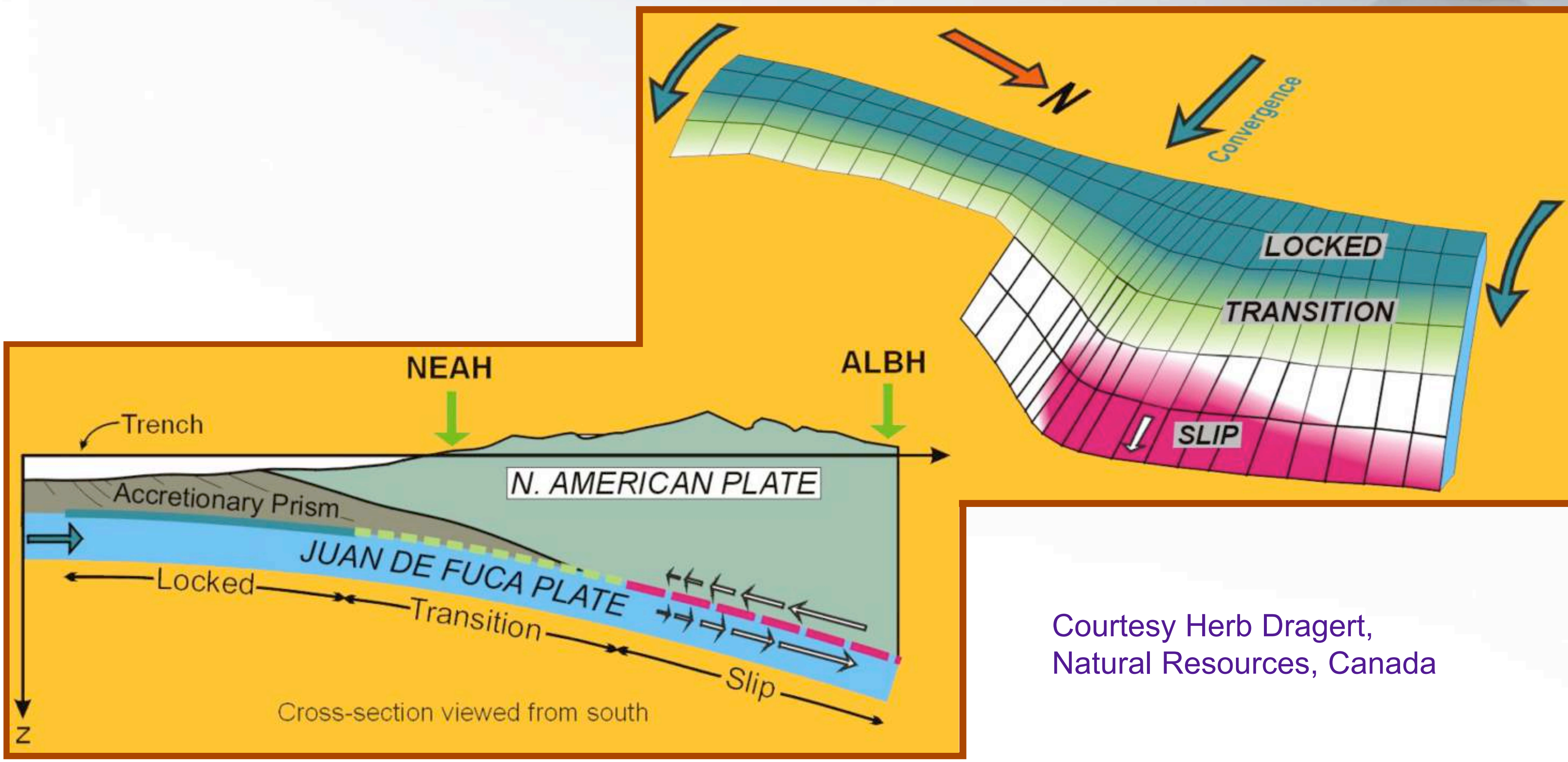
Slow "earthquakes" are observed in Cascadia and Japan along the subduction zones.





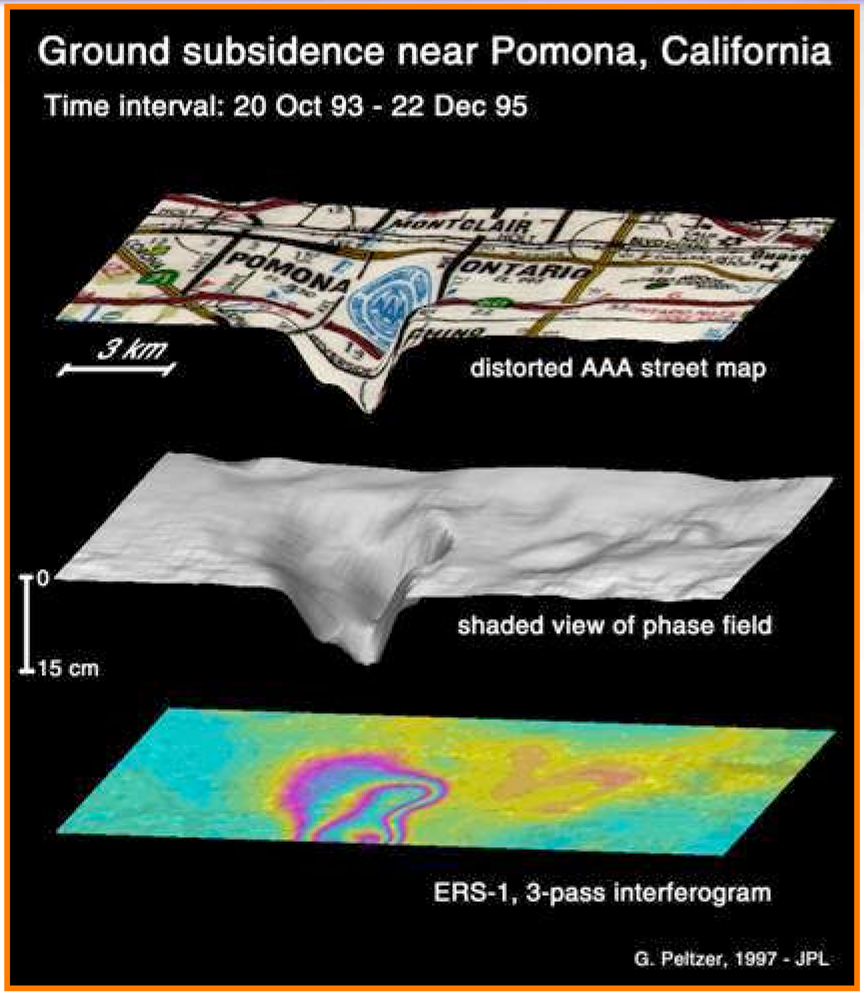
In Canada, these events take about 15 days, propagate northward, and occur every 16-18 months.

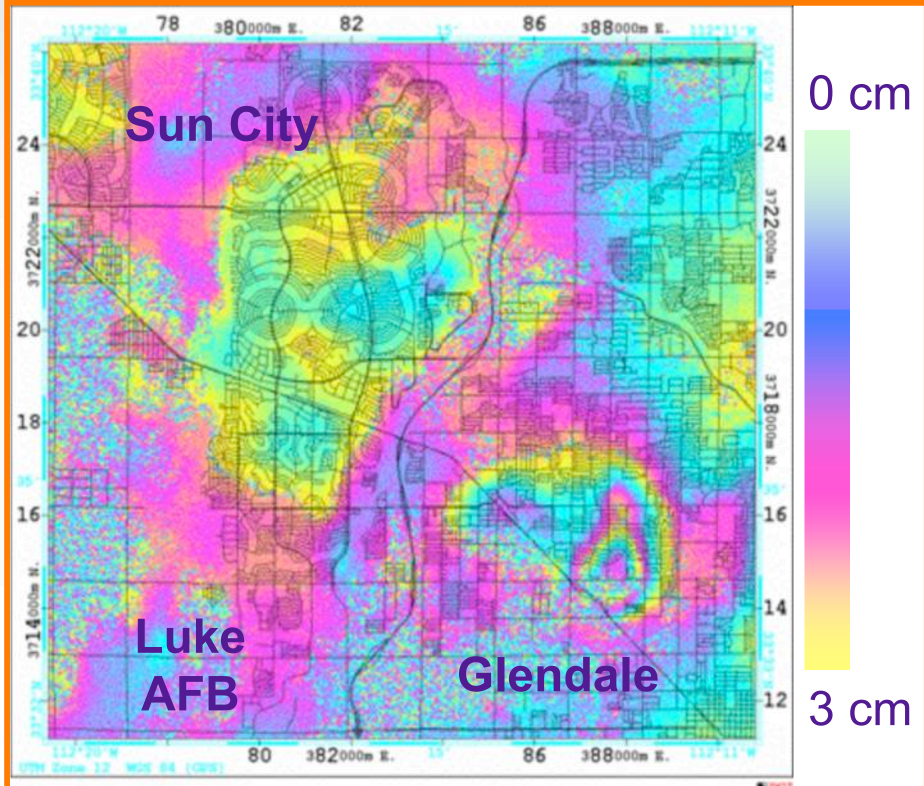
Slip Occurs on the Deep Part of the Subduction Zone



Courtesy Herb Dragert,
Natural Resources, Canada

Land Subsidence





Produced by Vexcel Corporation under NASA's State & Local Partnership Program, John C. Stennis Space Center.

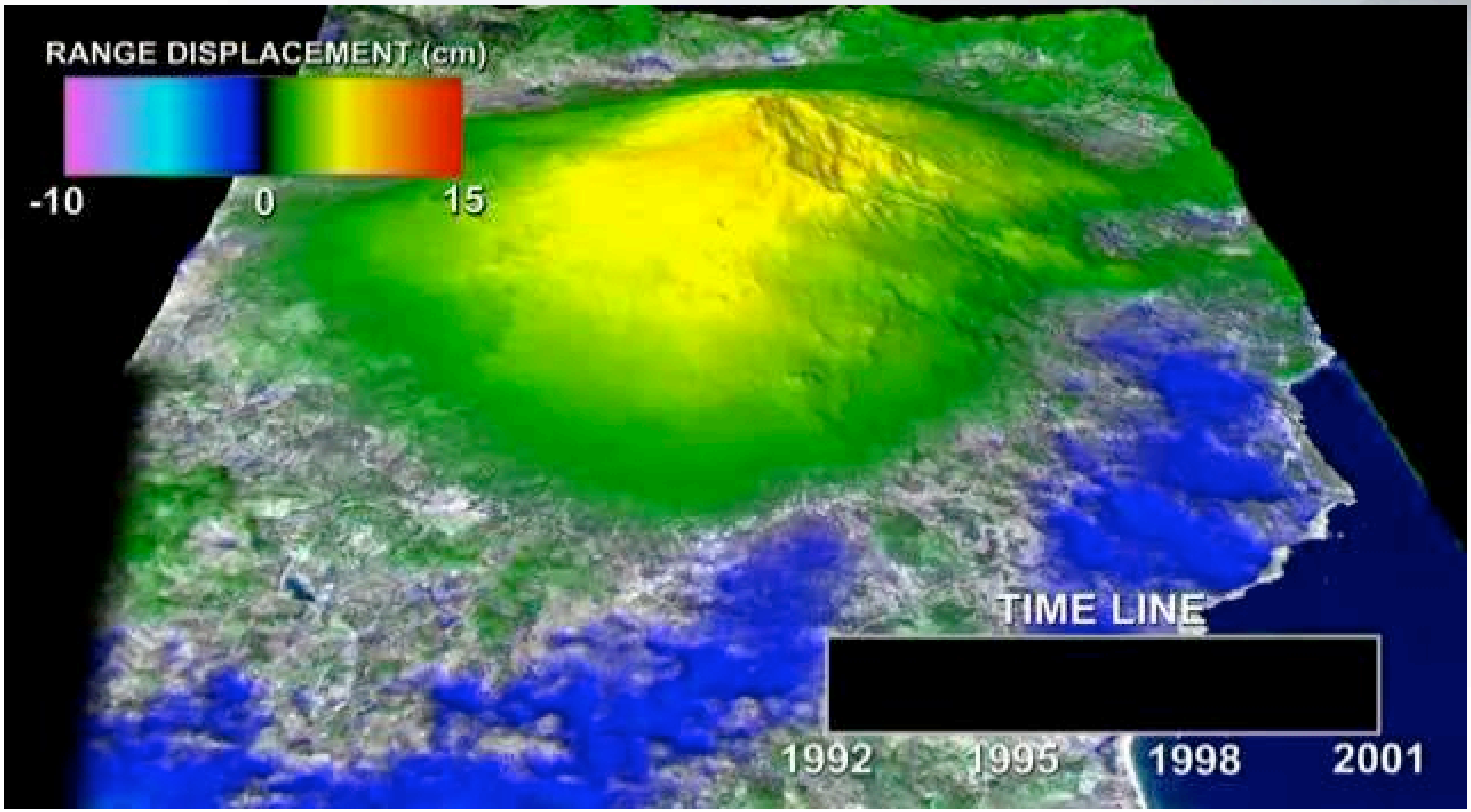
Measurement of crustal deformation is also used to detect land subsidence: sinking of the land due withdrawal of water and oil.

Jet Propulsion Laboratory
California Institute of Technology

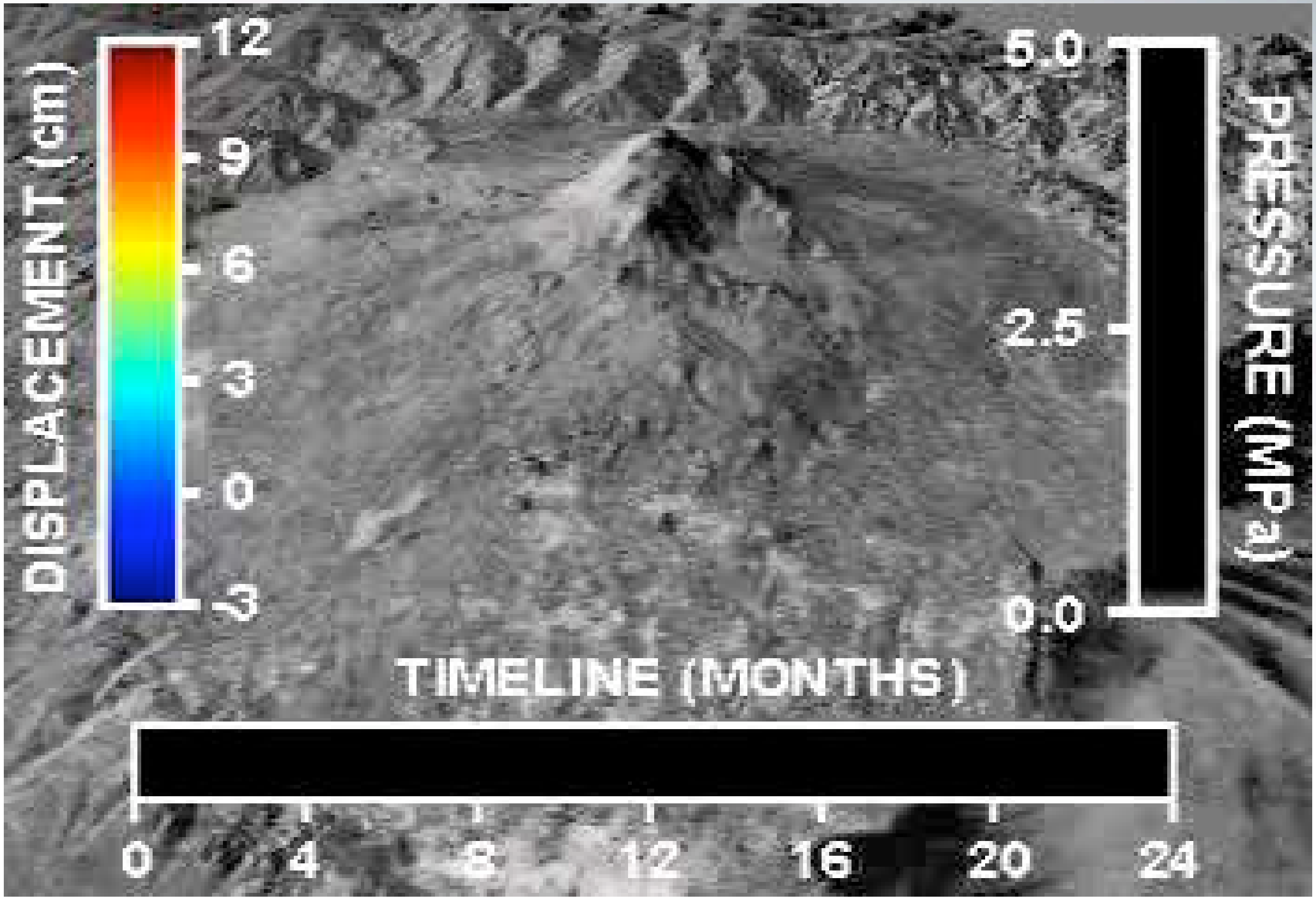
Lost Hills Land Subsidence

Jet Propulsion Laboratory
California Institute of Technology

Mount Etna Surface Deformation

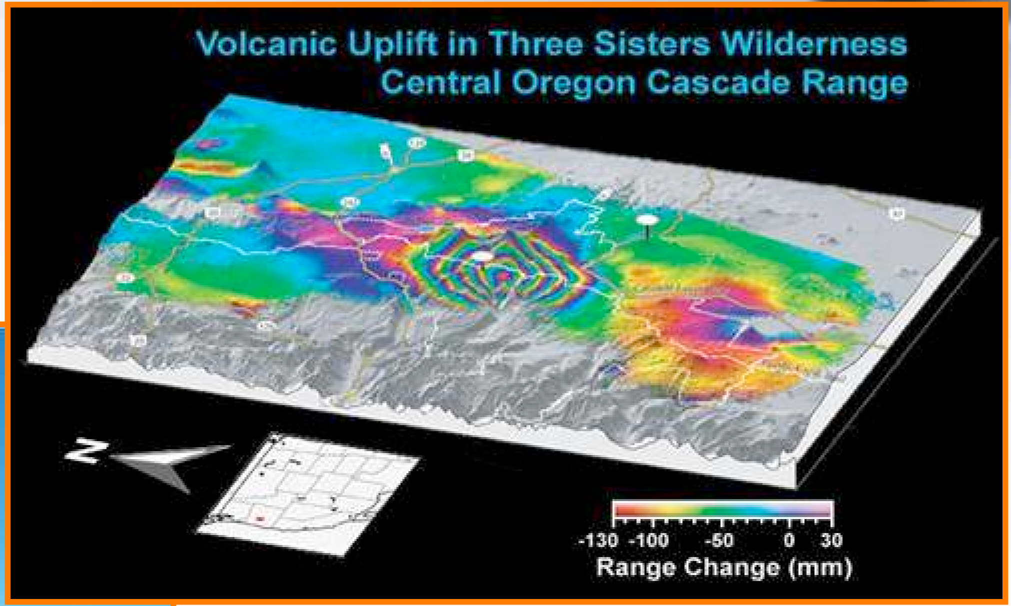


Mount Etna Deformation



Three Sisters Volcanic Uplift

Observed uplift of 4 cm/yr is due to magma injection at a depth of 8 km.

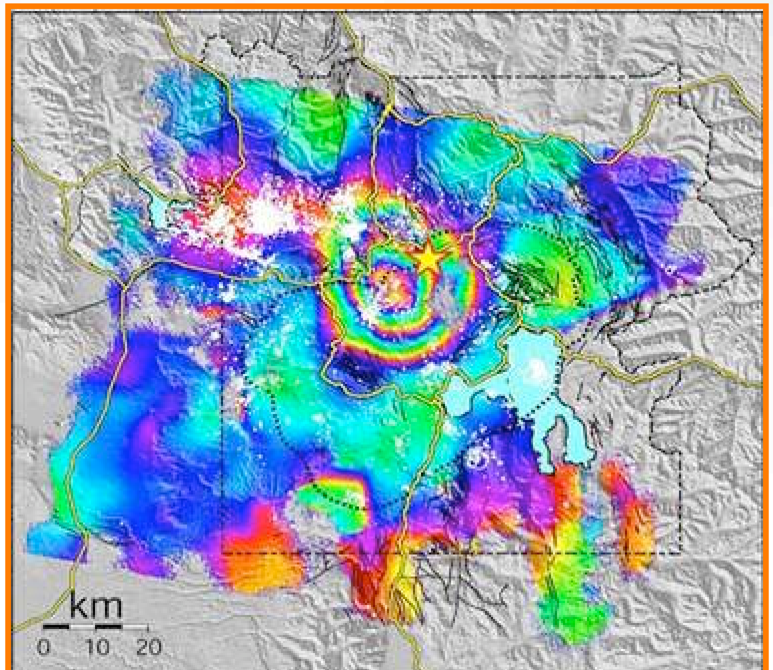


Courtesy Wayne Thatcher, USGS

Jet Propulsion Laboratory
California Institute of Technology

Yellowstone Thermal Unrest

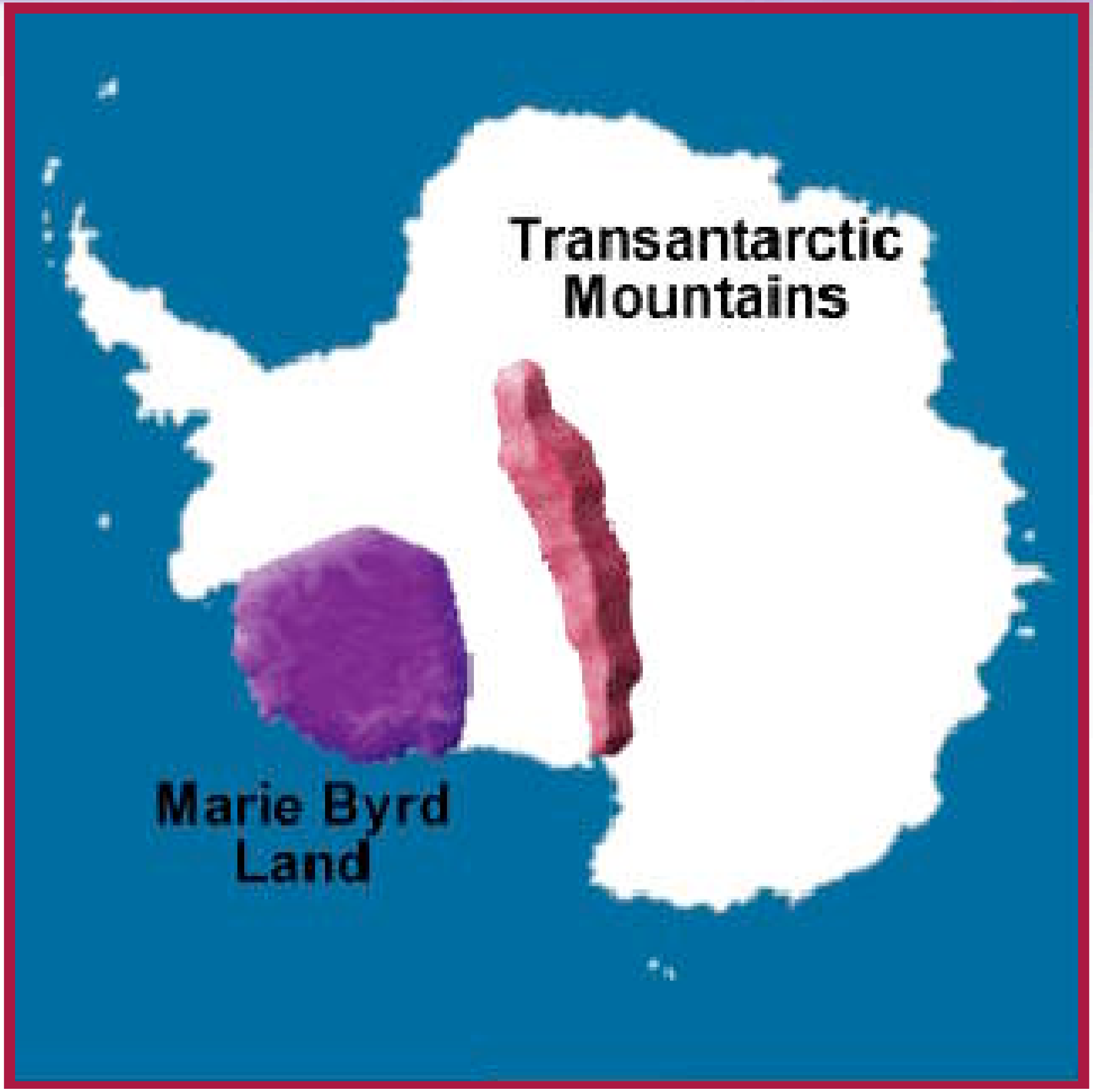
Steamboat geyser which normally erupts every 10 years has erupted 3 times since 2000. This is due to injection of hot fluid rock at a depth of 18 km.



Courtesy Wayne Thatcher, USGS

Jet Propulsion Laboratory
California Institute of Technology

Studying Antarctica

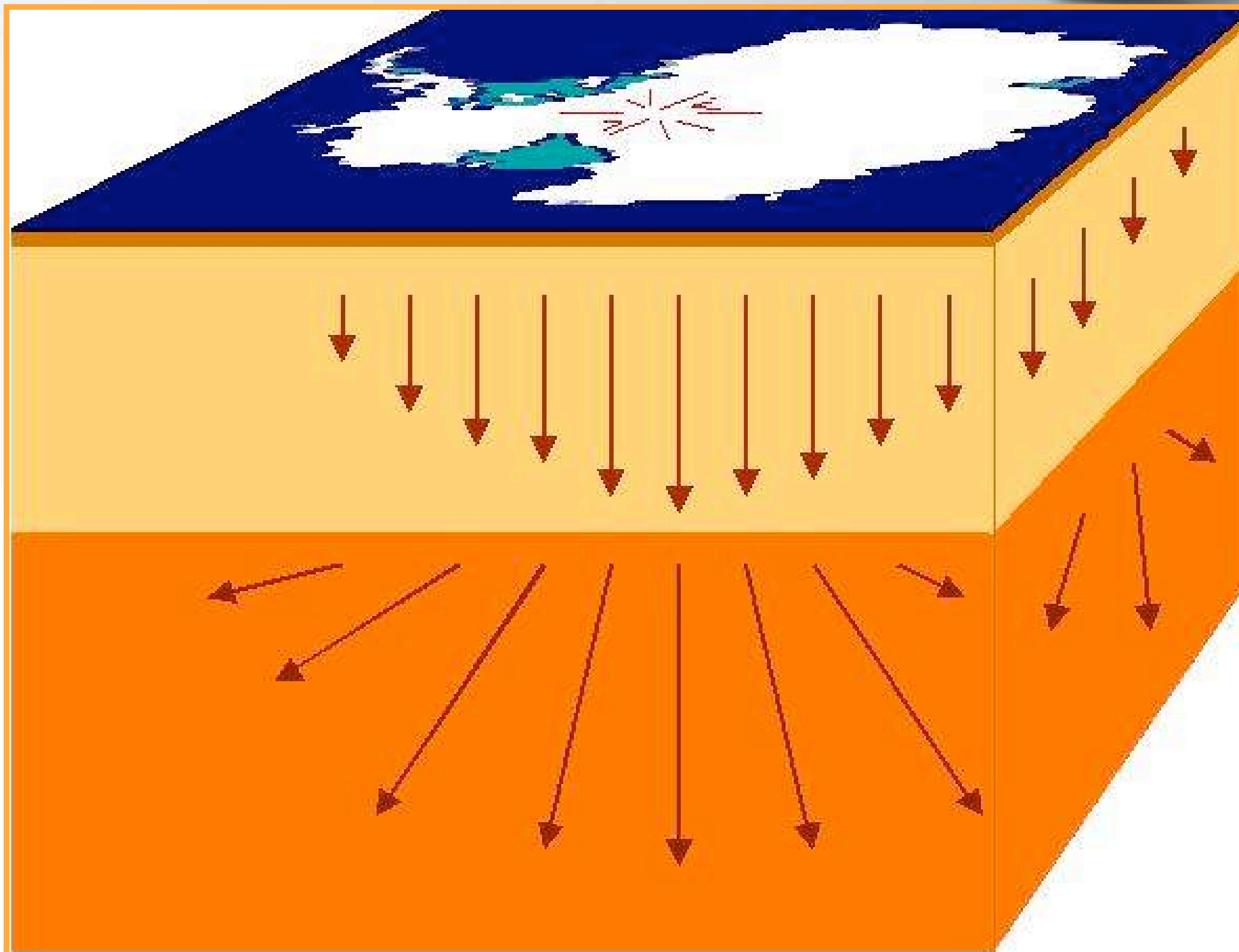


Jet Propulsion Laboratory
California Institute of Technology

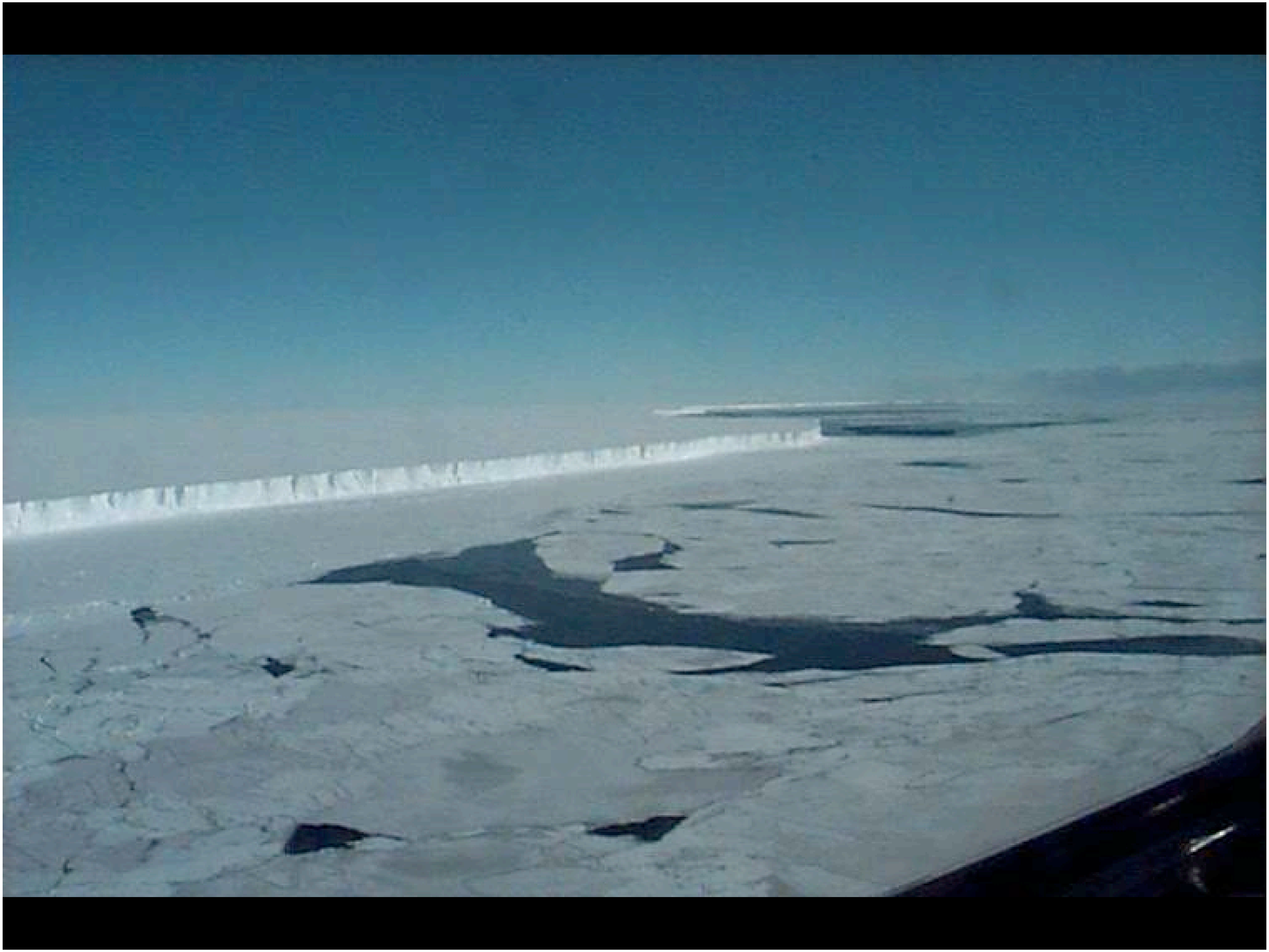

UNITED STATES ANTARCTIC PROGRAM
WELCOMES YOU TO
McMURDO STATION

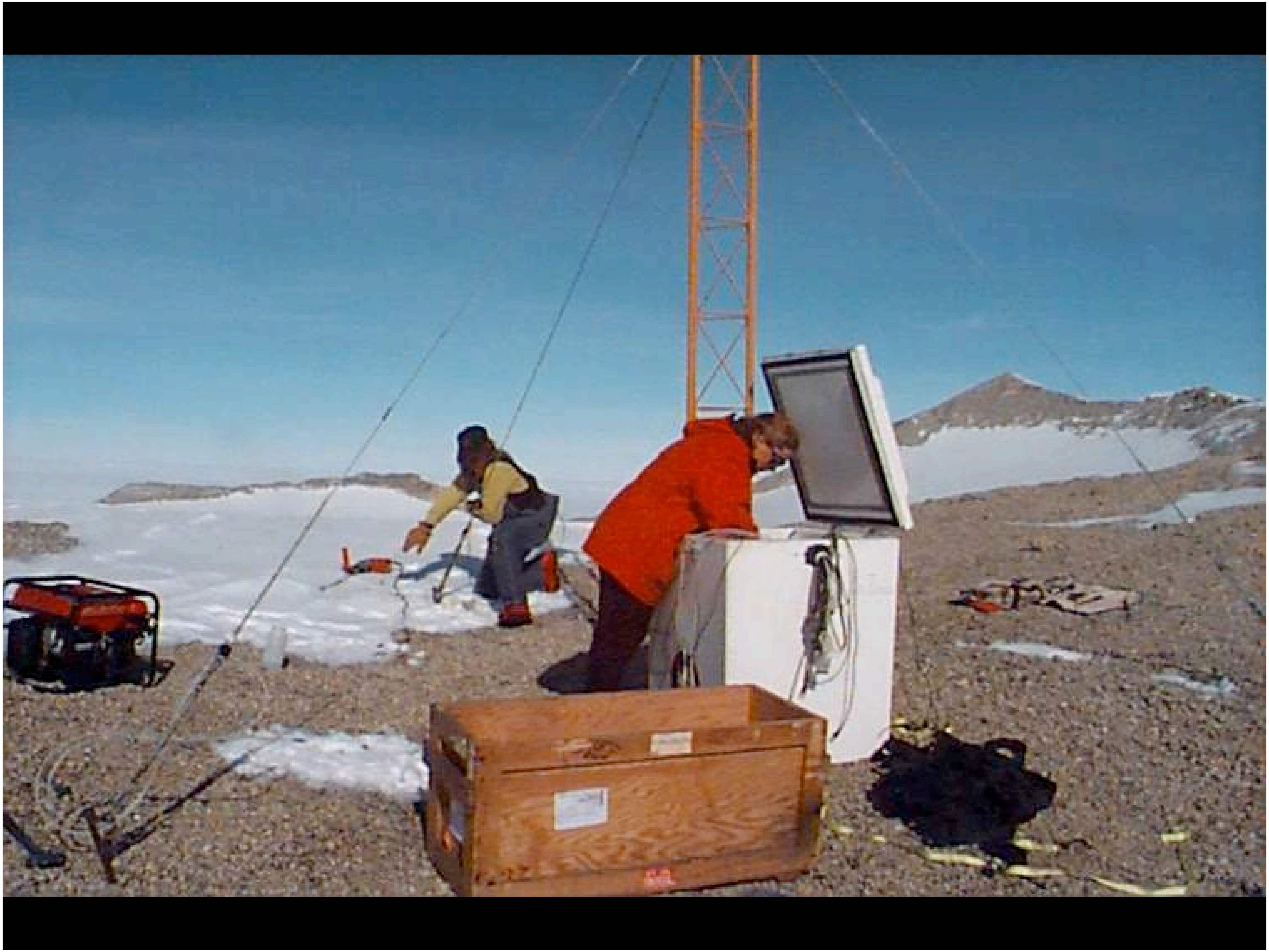
Post Glacial Rebound

- The thick ice sheet pushes down on the earth
- As the ice thins the mantle flows back
- The surface of the earth rebounds



Jet Propulsion Laboratory
California Institute of Technology

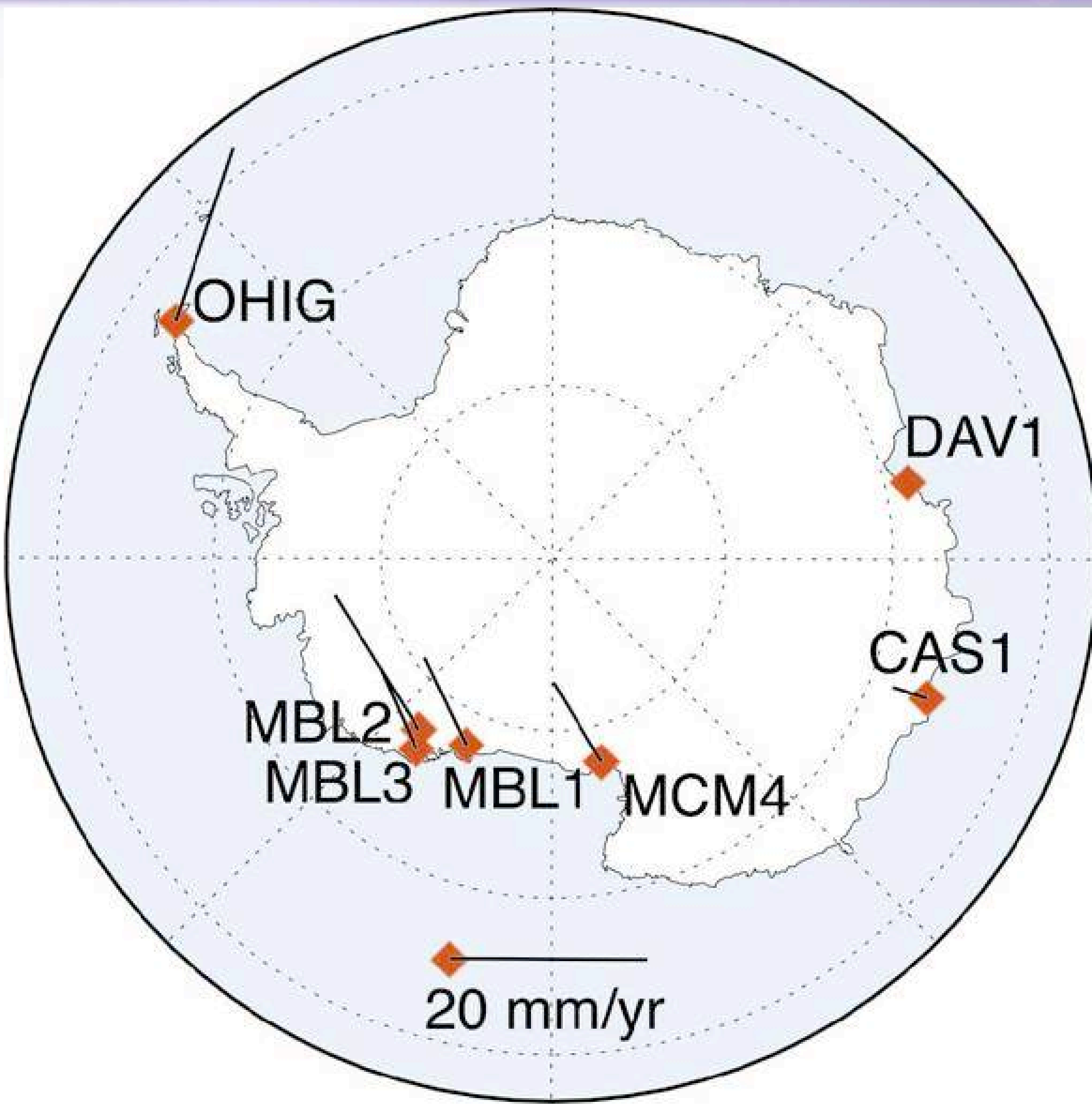




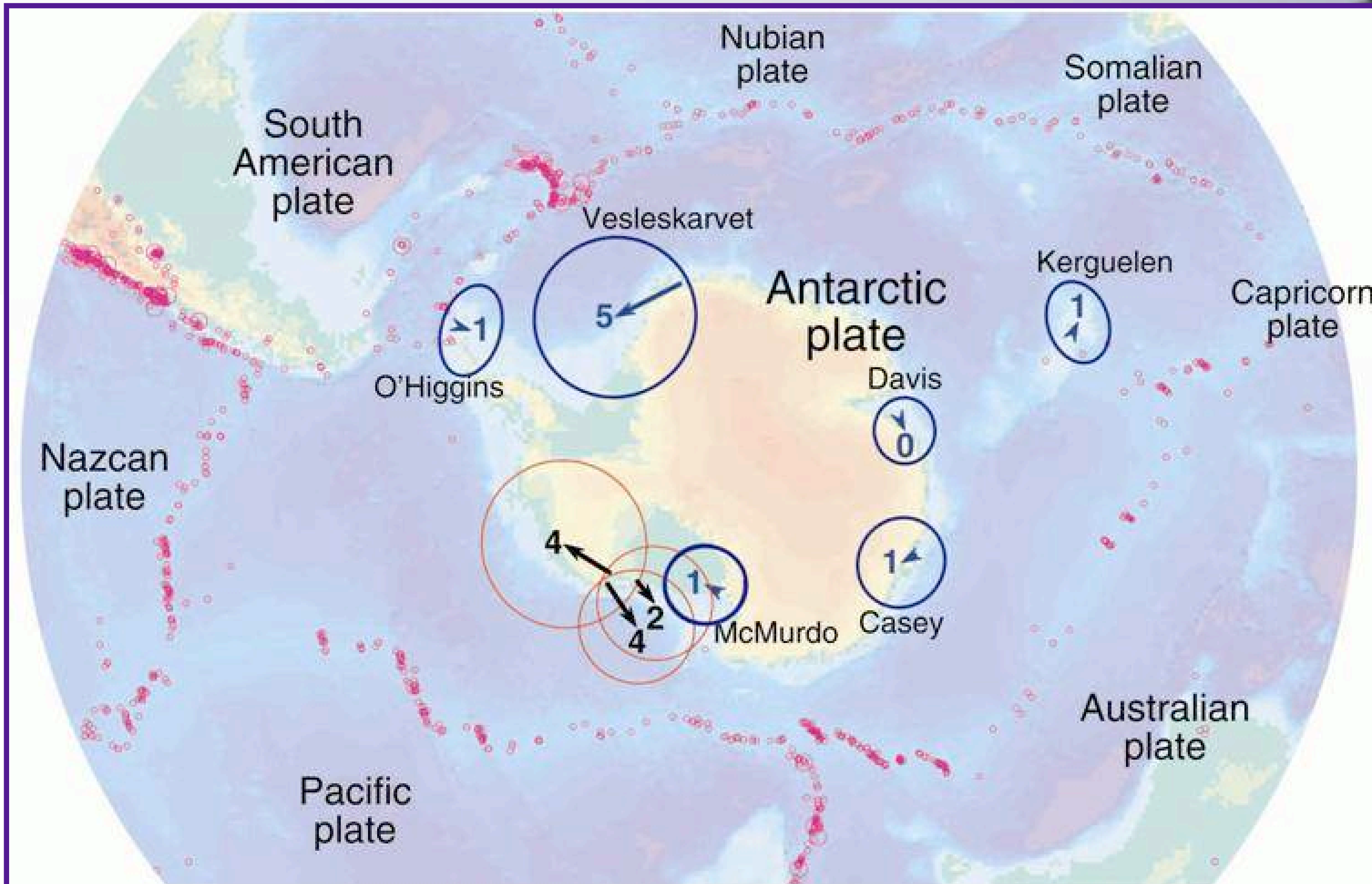

Cafe
La Ford


E.W.NE

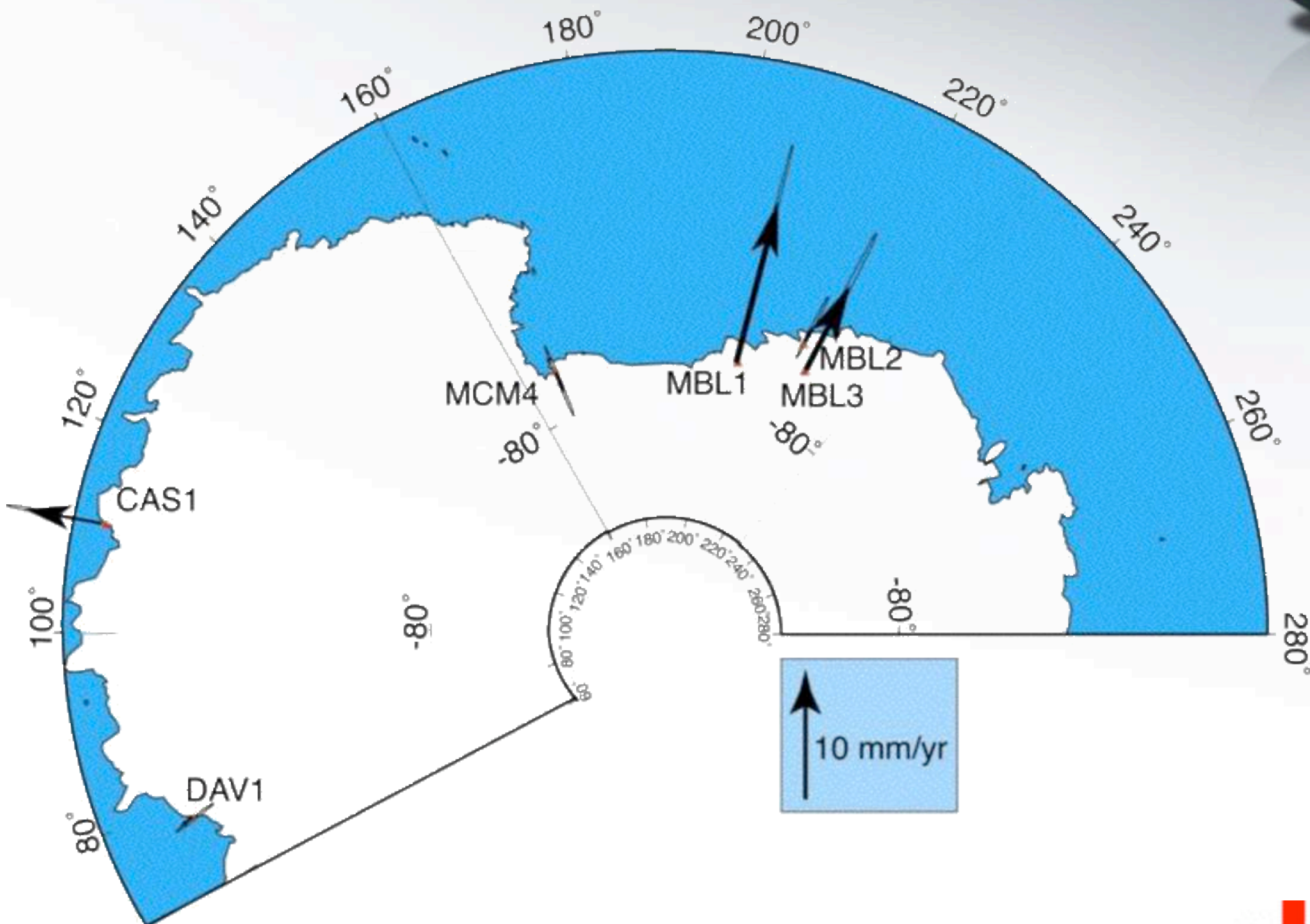
Absolute Horizontal Velocities



Residual Horizontal Velocities



Vertical Velocities



Measuring Shorelines to Study the Inside of the Earth

The Altiplano, Bolivia

California Institute of Technology

Earthquakes in Continents
Mongolia

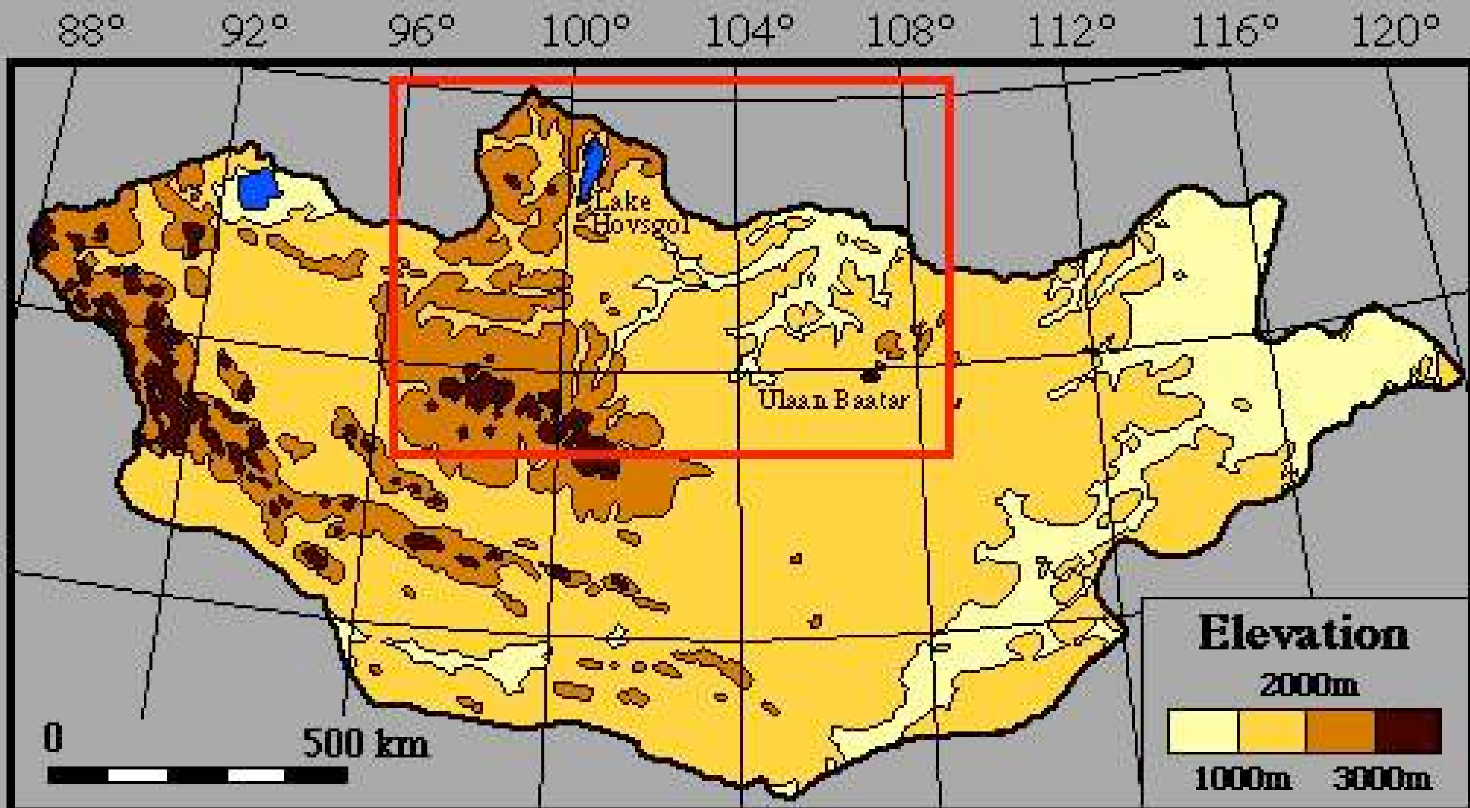


Figure 1: Elevation map of Mongolia. The red box designates the territory covered on our reconnaissance trip in September, 1996. See below for details of the trip route.

Jet Propulsion Laboratory
California Institute of Technology

Bulnay Fault *1908 Rupture*

Jet Propulsion Laboratory
California Institute of Technology

Global Earthquakes 1960-1995

Jet Propulsion Laboratory
California Institute of Technology

Measurement of Crustal Deformation is the Highest Priority

"InSAR (Interferometric SAR) provides a means of measuring and monitoring the motion of the Earth's surface in great detail over wide areas, and should be regarded as an essential component of EarthScope"

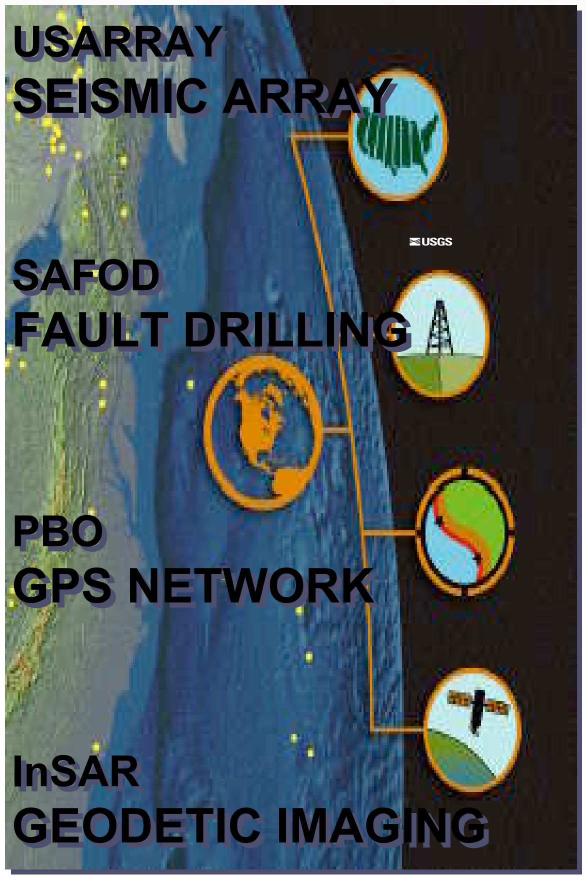
National Research Council

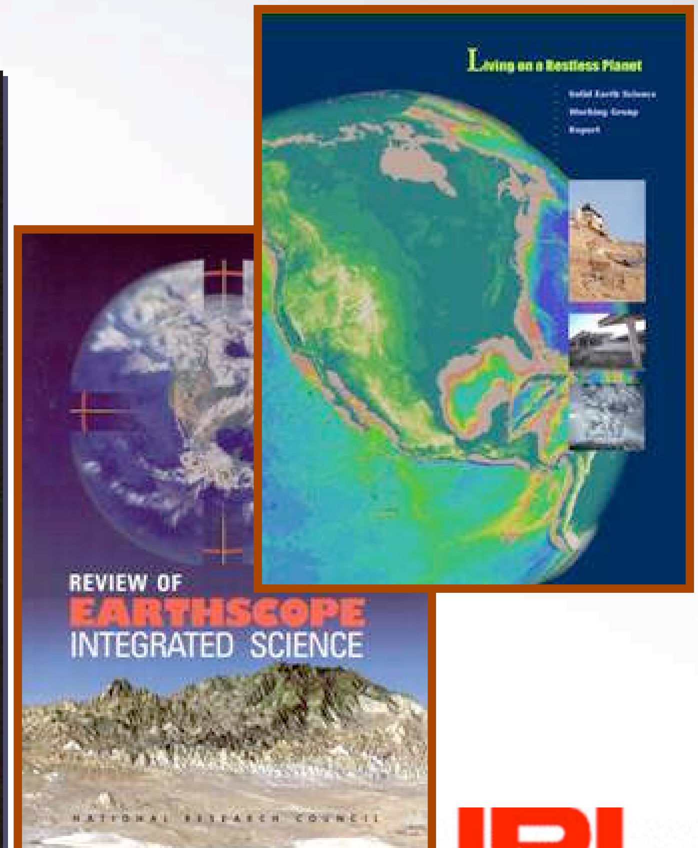
"What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?"

Weekly surface deformation maps from InSAR are the highest priority.

NASA Solid Earth Science Working Group

EARTHSCOPE



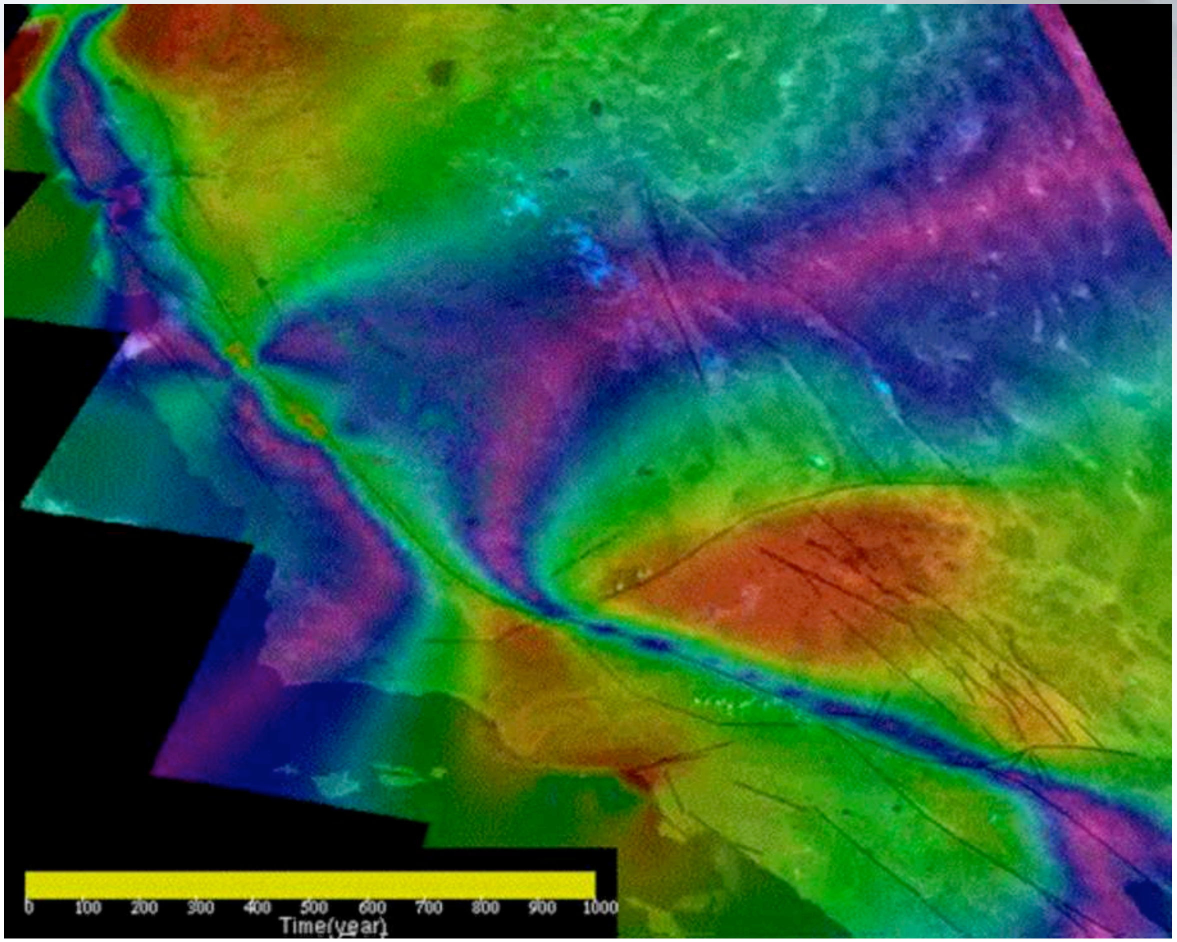


USGS science for a changing world

JPL
Jet Propulsion Laboratory
California Institute of Technology

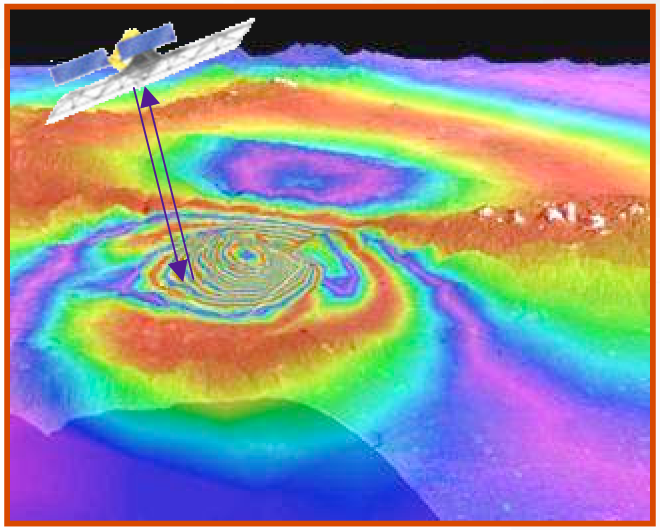
1000 Years of Simulated Earthquakes

Global InSAR data will result in observations of hundreds of earthquakes per year, vastly improving our understanding of earthquake processes.



Jet Propulsion Laboratory
California Institute of Technology

Summary



InSAR is the key to unlocking earthquake secrets.

Serendipitous measurements of crustal deformation show previously unknown active regions and are illuminating the underlying processes.

Measurement of crustal deformation and new computational methods will refine hazard maps from **100 km and 50 years** to **10 km and 5 years**.

Jet Propulsion Laboratory
California Institute of Technology